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10-KILOCYCLE LONG-RANGE SEARCH SONAR

[Unclassified Title]

H. L. Saxton, H. R. Baker, and N. Shear

Sound Division

August 19, 1955

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ABSTRACT

An experimental echo-ranging equipment has been developed, utilizing a searchlight transducer of seven square feet in area, capable of 5-kw acoustic power, and operating at a frequency of 10 kc. Improved receivers and displays have also been incorporated. This equipment was installed in a submarine which offered the greatest flexibility as a research platform for investigating the capabilities of the system, and for the optimum utilization of acoustic paths.

Results of operational research with the system, carried out in the period February 1951 to April 1952, were better than predicted. The average echo range from submarine targets in surface-bounded ducts was 18.5 kyd with a maximum echo range of 41 kyd. Transmission loss in surface bounded ducts was of the order of 1 db/kyd. Transmission loss by way of the bottom-reflected and skip-distance paths was too great to permit long-range detection, but knowledge obtained from a study of these paths indicated that they might be used effectively at lower frequencies, with high source levels. Reverberation was not found to be a limiting factor. Research with the 10-kc experimental equipment indicates that the basic concepts on which it was designed were sound and that even greater detection ranges than had previously predicted are possible by using lower frequencies and making optimum use of the various acoustic paths.

PROBLEM STATUS

This is a final report on one phase of the problem; work is continuing on other phases.

AUTHORIZATION

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I - BASIC CONSIDERATIONS

INTRODUCTION

By 1948 it was glaringly apparent that fleet sonar equipment was inadequate to cope with the antisubmarine problem. This situation was caused by the advent of the faster submarine and the recognized possibility of the use of long-range torpedoes by the enemy. There was then a lack of optimism on the part of scientists that ranges by active sonar could be extended several fold, the improvement that seemed necessary.

Early in 1948, ONR initiated a study of the sufficiency of sonar equipments to solve the problem. This study culminated in a report (Ref. 1). It was then apparent that old concepts gave little promise of solving the problems because they assumed a high percentage of conditions in which enemy submarines would be operating in shadow zones, that is, in regions to which no acoustic path existed. However, there was a ray of hope from reports of the existence of submerged ducts, and the possibility of using reflections from the bottom of the ocean to provide an acoustic path.

The problem of long-range search taken on by the Naval Research Laboratory was aimed primarily at studying long-range possibilities. Such a study necessitated the design and construction of instrumentation in the form of a sonar equipment as a research tool to permit learning more about the characteristics of the ocean which affect sound propagation. This same equipment had possibilities of establishing the feasibility of obtaining long ranges and of indicating the necessary design parameters for future fleet equipment.

This is a final report of the work carried out by the Naval Research Laboratory involving preliminary studies, the design of instrumentation, operations at sea, data taking, analysis, and recommendations.

PRELIMINARY ANALYSIS

The preliminary analysis of the possibilities of long range detection was carried out at a time (1948-49) when our knowledge of sound propagation in the ocean was greatly limited relative to the present. Nevertheless, the theory used gave predictions which proved fairly indicative of results to come, though inclined toward conservatism within the range of performance actually obtained. For the record, and for comparison with the analysis of data appearing later in the report, a brief summary of the method used is given. A more complete treatment is given in Ref. 2.

Acoustic Paths

At the outset it was obvious that targets could not be detected unless an acoustic path existed through the water from the sound transducer to the target. At that time, to penetrate shadow zones by brute force methods was considered hopeless. Second, the necessity of going to lower frequency was obvious since it appeared utterly unfeasible to buck attenuations of 3 to 5 db per kiloyard which characterized the frequency range of 18 to 25 kc. Third, a very simple analysis revealed the necessity for improved equipment parameters, preferably all three basic parameters: power, transducer diameter, and sensitivity of the receiver (commonly expressed in terms of a recognition differential).

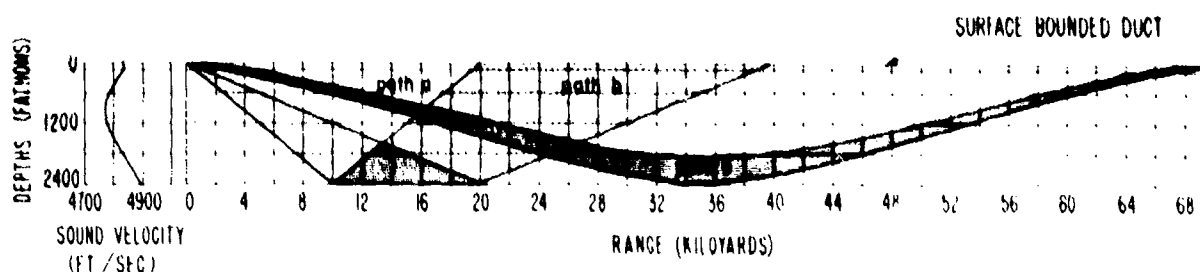
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Figure 1 - Three acoustic paths

Acoustic paths worthy of consideration appeared to be the surface-bounded duct, the path via the bottom, the skip path, and the submerged duct. The first three of these are shown in Fig. 1.

The surface-bounded duct arises when surface mixing equalizes the temperature at different depths down to some such depth, as 100 or 200 feet, known as layer thickness. In this single-temperature layer, sound experiences upward refraction because of the increased velocity of sound with pressure, or depth.

Ray paths are arcs of circles. A cycle of travel is the travel between the two points at which an arc intersects the surface. The reflected ray then starts another arc and the ray continues through successive cycles. This constitutes trapping. Any ray penetrating below the layer experiences pronounced downward refraction and is lost in the deeps. In the trapped mode of propagation, only cylindrical divergence is experienced after approximately the first kiloyard. The two-way divergence loss is therefore $40 \log 1000 + 20 \log R$ decibels, where R is the range in kiloyards. Attenuation represents additional loss. As an example, if the attenuation is assumed to be 1.5 db/kyd, a total loss of 192 db at 16 kiloyards range is calculated. This assumed attenuation is obtainable at a frequency of about 10 kc.

The path via the bottom is substantially a path involving spherical divergence all the way. The divergence loss is $40 \log 1000 + 40 \log R$ in which R is slant range in kiloyards. Attenuation and reflection loss must also be considered. Assuming a reflection loss of 10 db each way and the same attenuation as for the previous case, a total loss of 195 db at 7 kyds slant range is calculated. Lower reflection loss, improved equipment parameters, or lower noise background could substantially improve this range. Consequently, prospects for substantially improved detection ranges appeared bright, and the inauguration of a strong research program in this field was regarded as sound.

The skip distance path is usually one of 35 miles, obtainable only in deep water. Rays near the horizontal are bent downward near the surface and then at greater depths are bent upward and return to the surface. Appreciable focusing in a vertical plane is experienced at the skip distance. Divergence loss is about $30 \log 1000 + 30 \log R$ and attenuation is assumed the same as before. The total loss over this path for the round trip is 385 db for these assumptions. This loss is prohibitive. It should be noted, however, that for lesser assumed attenuation, obtainable at frequencies well below 10 kc, the path offers possibilities.

The submerged duct may arise when surface heating produces a negative-gradient layer surmounting a single-temperature layer. Other instances have been observed where a duct exists at a depth of a hundred or a few hundred feet. This case was not treated differently than the surface-bounded duct at the time of the preliminary analysis.

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The suspicion that submerged ducts were not infrequent and the need for definite information on the effects of transducer depth led to an early decision, in which OpNav concurred, that a submarine would be the vehicle chosen to carry the experimental equipment.

Use of Low Frequency

The formula used in 1948 for attenuation over all acoustic paths was $\alpha = 0.028f^{1.73}$ db/kyd with f in kilocycles. This formula was descriptive of curves reported in the NDRC Technical Summary Reports (Ref. 3) fitting data obtained at higher frequencies than feasible for long range, but representing what seemed to be the best available data at that time. This formula gives $\alpha = 5$ db/kyd at 20 kc, 1.5 db/kyd at 10 kc, and 0.5 db/kyd at 5 kc. The reduction of loss by 3.5 db/kyd each way in going down in frequency from 20 kc to 10 kc, represents a reduction of 70 db in the loss to 10 kyds and return. From one point of view, this seemed a very easy way to pick up 70 decibels, but perhaps a better way to look at it is that the 70 decibels higher loss is prohibitive of long ranges at 20 kc. The next halving of the frequency gains much less, -20 decibels at 10 kiloyards. However, if one were trying for ranges of 20 kiloyards or more, this difference in loss between 5 kc and 10 kc would go up to 40 db or more and certainly would be important. As a matter of fact, it was concluded by this Laboratory that a choice of frequency of 5 kc was highly desirable. Only the inability to produce or procure a suitable transducer in a reasonable time led to the relinquishing of this choice. The 10-kc transducer, which appeared to offer the best compromise between low attenuation and immediacy, was therefore chosen. Work leading to a 5-kc transducer design, however, was immediately initiated.

Equipment Parameters

There seemed to be a tendency on the part of some to regard the problem as only one of going to low frequency. The Laboratory demonstrated in reports (see Ref. 2) that low frequency by itself would gain little or nothing. This can be reiterated as follows. Suppose that we wish to compare the performance of a 10-kc equipment with a 20-kc equipment having a range of 2500 yards, both equipments having the same transducer area and the same power output. At one-yard range, the 20-kc equipment produces a 6 db higher sound intensity because of its higher directivity. Add to this the fact that background noise is 5 db lower to start with at 20 kc, and the loss at 10 kc relative to 20 kc totals 17 decibels at 1-yard range. Now, at 7 db per kiloyard gained by the 10-kc equipment, relative to 20 kc, this equipment gains back 17 db in 2500 yards and, at that range, is just equivalent to the 20-kc equipment. If then 2500 yards is the limiting range for the 20-kc equipment, it is also the limiting range for the 10-kc equipment. But note that whereas an increase in range from 2500 yards to 10,000 yards would require equipment improvement at 20 kc of 99 db, of which 75 db compensates for higher attenuation loss, it would require improvement at 10 kc of only 46 db, of which 22 db compensates for higher attenuation loss. The combination of lower frequency and improved equipment is absolutely essential if long ranges are to be obtained.

Mathematical Formulation of the Problem

It is now possible to compute the equipment requirements to permit acceptance of a loss of 190 to 195 decibels previously calculated in examples given for paths in surface-bounded ducts and via the bottom. This requires the formulation of the echo-ranging equation, in simplified form.

Let us first define echo excess, E , as the excess in decibels of the echo level over the level required for a 50% probability of detection. The echo ranging equation is

$$E = E_1 - \text{losses} \quad (1)$$

where E_1 is the hypothetical echo excess at a range of one yard. At the particular range where the losses are equal to E_1 , the echo excess, E , is zero and there is a 50% probability of detection.

The delineation of E_1 is contained in the following equation.

$$E_1 = (I_1 + T) - (N - \Delta + \delta) \quad (2)$$

in which

I_1 is intensity at one yard from the source*

T is target strength

N is omnidirectional noise in a one-cycle band

Δ is the directivity index which rejects part of the noise

δ is the recognition differential (i.e., ratio of signal to noise in a 1-cps band at the transducer output required for a 50% probability of detection)

Target strength was assumed to be 10 db from reports that it varied from 0 db to 25 db depending on aspect. The noise of a 15-knot destroyer in a 1-cps band at 10 kc is -40 db.* δ was tabulated for 1/2 sec. pulses** as 17 db in Ref. 3. Using these values together with an E_1 of 192 db (the loss which must be sustained), Eq. (2) yields

$$I_1 + \Delta = 192 - 10 - 40 + 17 = 159 \text{ db.} \quad (2a)$$

Equation (2a) showed that the equipment would have to be good enough so that the intensity at 1 yard from the source plus the directivity index would add to give 159 db. This appeared feasible.

A convenient method of presenting the echo-ranging equation in graphical form for a comparison of range predictions for different equipments at different frequencies is illustrated in Fig. 2, where echo excess is plotted against range. The predicted range at which there is a 50% probability of detection is the range at which the curve falls to zero. The assumed 10-kc equipment yields the equipment curve appropriately marked and predictions check the previously given calculations. Improvement resulting from say 10 db higher value of E_1 is readily observable by reading the range at which the 10-kc curve has a value of -10 db.

A 20-kc equipment having the same transducer diameter (3 ft.), the same power, and the same recognition differential is also represented. The superiority of this curve at short range is observable. The predicted range for this case is seen to be much less

*Relative to the intensity corresponding to an rms pressure of one microbar

**Actually -13 db was used but this was relative to a 1000-cps band of noise, which accounts for the 30-db difference

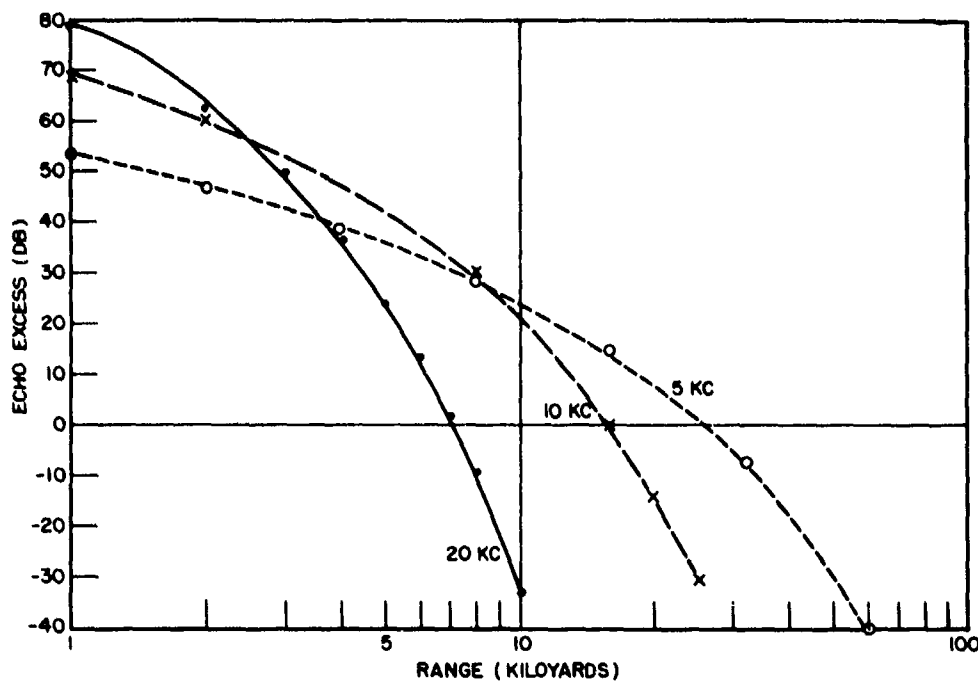


Figure 2 - Dependence of echo excess on frequency. Echo excess is calculated for three possible LRS sonars. All parameters except frequency kept constant.

than for 10 kc, however, since the curves cross at about the 2500-yd range. Finally, the 5-kc curve is observed to show some improvement over the 10-kc curve. It may be appreciated that higher values of E_1 for both these frequencies, raising the equipment curves by the same amount, would lead to a prediction of even better relative performance by the 5-kc equipment.

Reverberation Limitation

Range limitation by reverberations appeared to be a distinct possibility. However, it was the opinion of this Laboratory that data sufficient for computation of reverberation levels in ducts were not at hand. Previous equipment, unable to produce the return of reverberations from beyond 5000 yards, could not yield information concerning reverberation in surface-bounded ducts since it usually requires about this range before any sort of equilibrium distribution of trapped energy in the duct is closely approached. Likewise, in deep water over the path via the bottom, no reverberations had ever been studied from the near-surface region insonified after the reflection. Such calculations as were made with assumed scattering coefficients gave no cause for alarm. Furthermore, one of the most effective means of preventing reverberation limitation, namely the use of a transducer with a high directivity index, was planned. Other methods of reducing or smoothing reverberations were available if they proved necessary.

CONCLUSIONS

Preliminary analysis demonstrated that long ranges (7 to 16 kyd) should be obtainable with feasible equipment when good ducts existed, provided that reverberation limitation

Continued



did not occur. The only way to find out whether reverberations limited the detection range was to build a long-range equipment and make observations. Other research objectives of the problem were the more accurate determination of attenuation, determination of bottom-reflection loss, determination of target strength, and, in general, the achievement of an understanding of the whole propagation problem. A development objective was the determination of the feasibility of obtaining long ranges at 10 kc with an equipment of size and weight acceptable to the fleet, and the specification of required equipment parameters.



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II - EQUIPMENT

INTRODUCTION

It was indicated in the previous chapter that within the limits of our 1948 knowledge of propagation, significant increases in range appeared probable. The next step is to show how the required equipment parameters were incorporated in an equipment design of 10 kc. This design was aimed at producing an echo excess at 1 yd, E_1 , of 217 db in the background noise of a state 2 sea. On a 15-knot destroyer, E_1 would be reduced 15 db but the value of 192 db assumed in previous discussions would still be exceeded. The components of E_1 were given in Eq. (2). Those over which the designers can exercise some control are intensity at 1 yd, directivity index and recognition differential. Target strength and background noise are also contributory to E_1 . Table 1 lists the values of all these quantities sought or anticipated and lists also, for comparison, the values achieved.

TABLE 1
Elements Contributing to E

Parameter	Design Magnitude (db)	Achieved Magnitudes (db)
I_1	137	131
T	10	20
-N	55	51
Δ	25	25
- δ	-10	-13
	217 Total	214 Total

To satisfy the requirements of Table 1, frequency, transducer area, power and recognition differential (the last of these being dependent on pulse length) had to be carefully selected. The frequency, 10-kc, was low enough to reduce attenuation to about one-quarter of that at 25 kc. The transducer area was about 7 square feet - nearly four times that of the largest fleet searchlight transducers. The transducer could handle up to 5-kw input power in pulses up to 1 second in length, and the power supply and driver provided ample power for these pulses. The efficiency of the transducer was 55 to 60 percent, permitting radiating up to 2.5 kw of acoustic power. With such power, the axial sound intensity was about 50 times that obtained with conventional equipment, or 17 db above that of conventional equipment. The recognition differential was improved by several decibels over that of the ear by scanning the outputs of multiple narrow-band filters and by a special multiple-ping technique.

As indicated in Chapter I, OpNav authorized the use of a submarine as the sonar vehicle. The equipment was mounted in the USS GUAVINA (SSO-362). To accommodate the necessary equipment, the greater part of the forward torpedo room of the GUAVINA

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was made available for the installation (the forward tubes had been removed in a previous SSO conversion). The forward torpedo room (Fig. 3) was, for practical purposes, a shipboard sonar laboratory. It contained all of the long-range search system except the topside installation (also shown in Fig. 3).

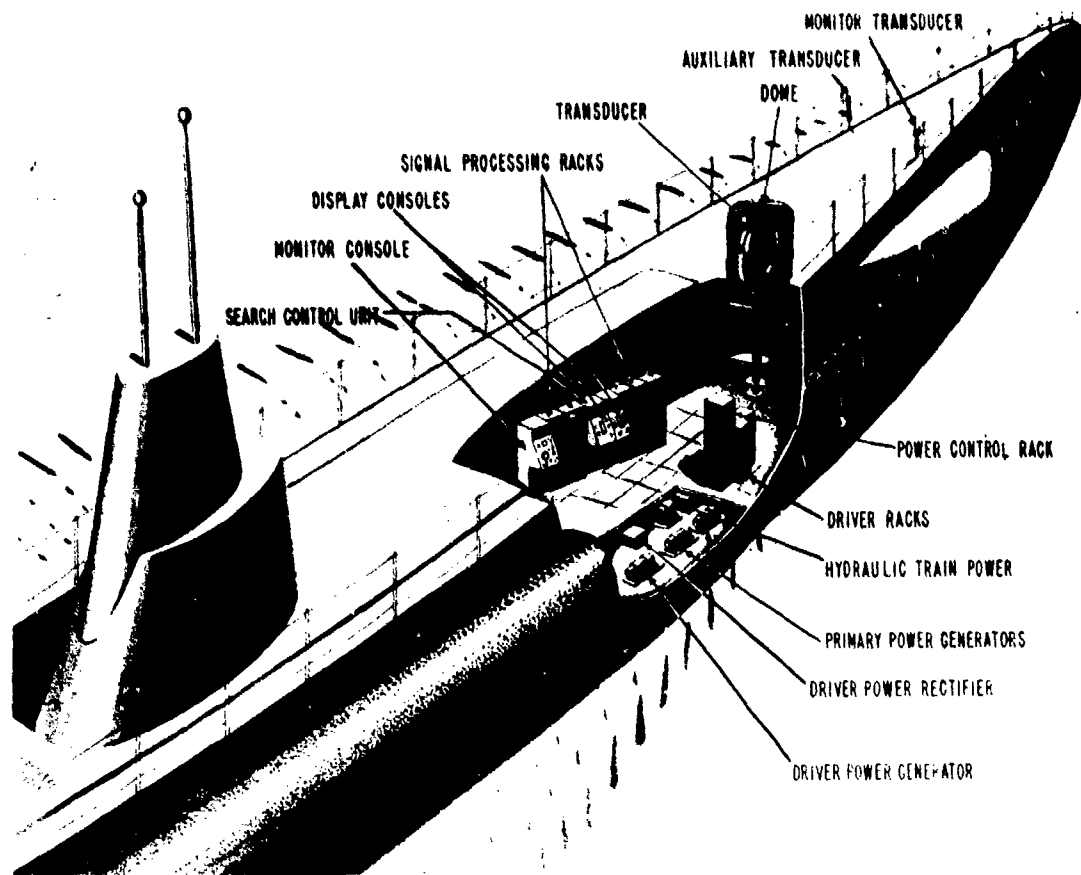


Figure 3 - Sonar installation on USS GUAVINA

SYSTEMS ELEMENTS

The system (Fig. 4) is described in Ref. 4. It consisted of: (a) a dome, (b) a transducer, (c) a search-control and training equipment, (d) a pulse generator with ODC and amplifier, (e) signal processors, (f) displays, (g) a power control and distribution system, (h) an equipment monitor, and (i) recording devices.

All electronic units mounted above the deck plates were of a standardized construction. This standard construction is similar to that of the telephone relay rack in that it is based on model panel size of 1-3/4 inches, all panels being some multiple of this width. Panels were mounted in the vertical plane with all tubes or other heat-producing components in the vertical duct formed between the panel and the back cover. A small blower forced air through this space for adequate cooling. All panels were mounted by hinges on the left side of the rack and could be opened easily for inspection. A removable

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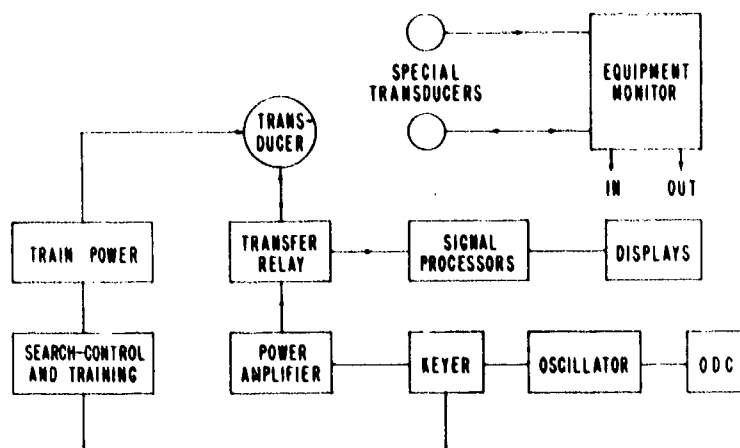


Figure 4 - Block diagram of LRS systems

cover over the front of the rack prevented accidental contact with electrical circuits. These units were designed to be of the maximum size which could be safely passed through a submarine access hatch.

Transducer and Dome

The transducer and dome were mounted topside, outside of the pressure hull (Fig. 5). The transducer and its mounting yoke, together weighing 3000 lbs, was mounted on the WFA topside training shaft. The standard carbon bearings for the WFA shaft had been replaced by Goodrich Cutlass bearings. In normal operation, the beam axis of the transducer was horizontal, but it could be tilted down manually to a maximum of 30 degrees in 5-degree steps. Tilting was accomplished by a turnbuckle arrangement which could be reached via an access door on the dome. Training in azimuth was accomplished by the search control and training equipment.

The active face of the transducer, three feet in diameter, was made of ADP crystals arranged in four vertical strips, each strip being divided into an upper and a lower half. Separate leads were brought out from each of these eight sections.

A cylindrical free-flooding dome, 5 feet in diameter and 8 feet high, provided protection for the transducer. The dome was of truss construction with a 36-mil, spot-welded, stainless-steel skin. A door facing aft permitted access to the transducer without removing the dome. Measurements showed a transmission loss of half a decibel through the dome and negligible distortion of the beam pattern.

Search Control and Training

The search-control unit was located above the Display Console 1 (Fig. 6).

To operate the transducer in search, the linear range of search, and a bearing search program needed to be selected. Range could be selected by the adjustment of the Long-Short switch, and the range selector knob. Any range from 2.5 to 15 kyds in 1.25-kyd. steps in the short-range position, and any range from 5 to 30 kyds in 2.5-kyd steps in the

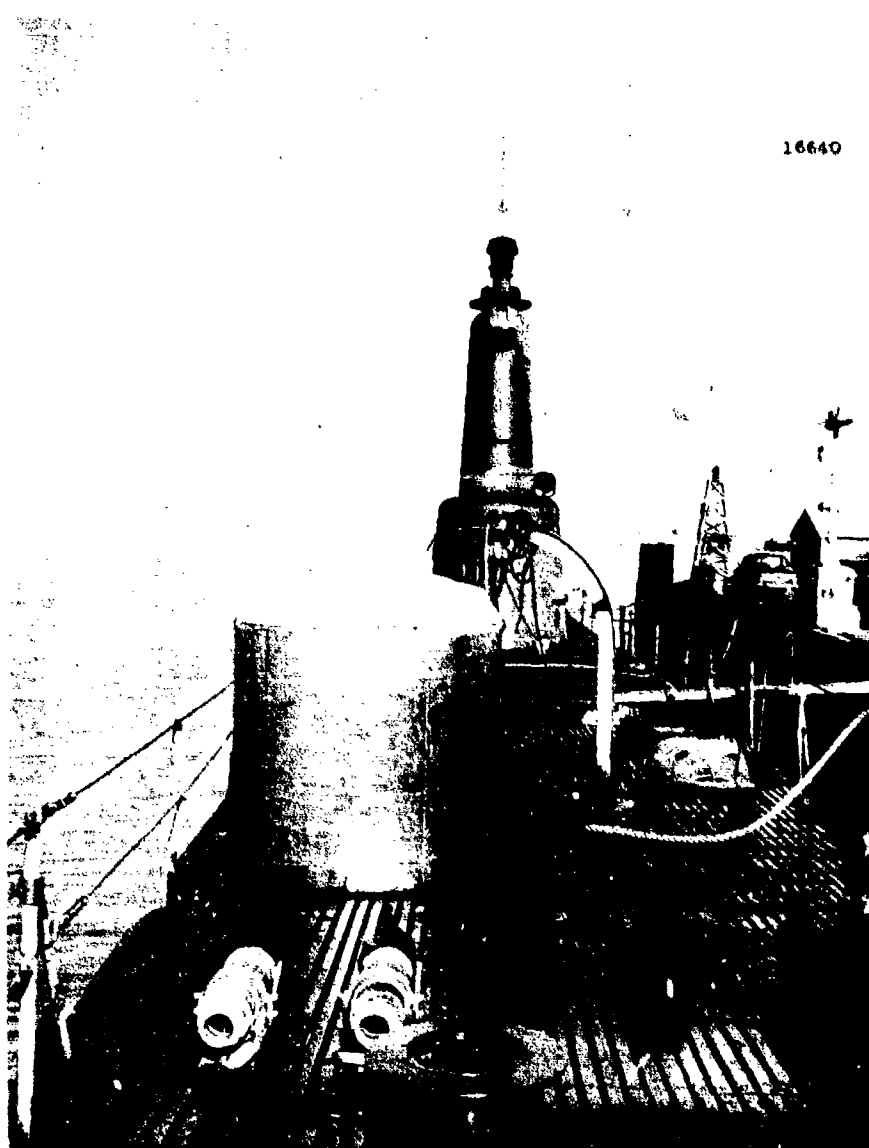
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Figure 5 - Transducer and dome mounting

long-range position could be selected. The ping repetition rate and the rate of the cathode-ray-tube range sweep corresponded to the selected range. Control of these quantities was consistent with the settings of the range.

In manual search, the operator trained the transducer with the handwheel shown at the lower right of Console 1. The operator could observe the true and relative bearings on the indicator directly above the handwheel.

When the automatic search mode of operation was desired, three quantities had to be selected: the search arc, the center of search arc, and the ping arc. The search arc is the total angular travel of the transducer during one search-sweep. This could be set between 90° and 180° . The center-of-search arc was set manually by the same handwheel used for training. The ping arc is the arc traversed between successive pings, and could be set between 3° and 9° .

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Figure 6 - Search control unit and display consoles

When these three parameters had been chosen and set, the operator threw a switch to "automatic" and the transducer then automatically trained continuously back and forth over the selected search arc at a rate which traversed the selected ping arc in the time determined by the selected range.

A Mark 5, Mod 9 hydraulic train unit was installed beneath the deck of the forward torpedo room. This unit contained its own amplifier and trained the transducer in accordance with the output of the search-control unit.

Pulse Generation and Amplification

The signal to be transmitted originated in an electronic oscillator. An own-doppler compensation unit varied the nominal 10-kc frequency as own-ship's speed and transducer-train angle were varied. The correction was such that reverberation always appeared at the same center frequency. A keyer unit formed a signal pulse from 0.01 to 1.0 sec in length, and delivered this pulse to the amplifier.

For electrical signal outputs up to about 4 kw with a pulse length of 0.5 sec, a low-power amplifier was the only one employed. This amplifier received its plate power from a conventional rectifier circuit, with capacitors providing electrical storage. (With shorter pulses somewhat higher power could be obtained.) When high power was desired,

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the low-power unit was used as a driver for an added final amplifier. This final amplifier was designed to deliver up to 40 kw in a 0.5-sec pulse at 10 kc.

Except in the output circuit, tuning was omitted from the amplifier stages, making it possible to operate over a band of frequencies limited only by the frequency characteristics of the transducer. Means were provided for measuring the transducer current, which could be adjusted to any desired value up to the maximum safe value for the transducer.

Signal Processing

Electric signals from the transducer's right and left halves were used as inputs to combining amplifiers. These combined the energy from the transducer halves, and provided electrically independent outputs, representing both the whole transducer and its halves, to the various signal-processing devices described below.

In signal processing, the objective is to treat the incoming acoustic energy in such a way as to enhance the signal-to-noise ratio. This may be accomplished by a different treatment of one part of the incoming energy which favors it with respect to the remainder. The signal processing devices which were used and tested are as follows.

The 10-KC Receiver - A conventional 10-kc receiver was used as a standard with which to compare other receiving equipments. Bandwidths of 50, 100, and 200 cps could be selected, and spot-tuning in 50-cycle steps could be accomplished when the 50-cps bandwidth was used. The receiver output went to a distribution panel, from which it could be connected to headphones at the operator's consoles, to a loud speaker, and to cathode-ray-tube displays.

The Sector-Scan Indicator (SSI) - The SSI is a phase-sensitive receiver which measures the phase angle between the electrical outputs of the two halves of the transducer. In the field, and simultaneously in the laboratory, this device has been further developed to bring out its optimum detection possibilities. The SSI assists in holding the transducer beam axis on the target and has application in target classification.

The Frequency-Scanning Receiver - The Frequency-Scanning Receiver offers a number of improvements over conventional sonar receivers for increasing the probability of detection of both noise-masked and reverberation-masked echoes, for presenting doppler information quantitatively as an aid to target classification, and for reducing operator fatigue. The equipment, and results of tests using the equipment, have been previously described (Refs. 5 and 6).

This receiver employs a set of narrow filters which performs a spectrum analysis of echo-ranging signals. The outputs of the individual filters are detected, and the resulting signal envelopes are sequentially sampled by a commutator. Information is presented on a B-scan cathode-ray-tube display with range as the ordinate, frequency or doppler as the abscissa, and signal amplitude as intensity modulation of the display.

The latest model of the FSR equipment was designed for use with the LRS equipment at 10 kilocycles. There are 29 adjacent filters, spaced 7 cps apart, each having a bandwidth of 7 cps. Range-rate information is thus presented directly in 1-knot increments over the range of target droppers from plus 14 knots to minus 14 knots. The resolution in range-rate is about 0.5 knot. Reverberations are attenuated by means of a sharply tuned notch filter, and the receiver gain is adjusted to the decay rate of the reverberation envelope.

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The Selective Time-Delay Receiver - A second device for improving the probability of detection of sonar echoes is the Selective Time-Delay Receiver. The system is modified to transmit a series of frequency-coded pulses and the received signals are selectively channeled by means of filters to a storage device. This system, as incorporated in the LRS research program, employs a multistylus chemical recorder for both the storage and the display of information. The series of echoes are presented side by side as a horizontally orientated pattern, while noise bursts and other interfering background components occurring simultaneously produce diagonal patterns on the display.

The Graphic Indicator - The Graphic Indicator is a device for comparing, over successive cycles, the phases of the echo and a calibrated, tunable local oscillator as a reference frequency. Its display is a B-scan of phase relationship versus time. This device permits high-precision measurement of doppler shifts.

The target echo is distinguishable from reverberation by a pattern of definite slope which differs from that of the reverberation when there is target doppler. Noise gives a random pattern. This instrument aids in the classification of targets.

Displays - The control operator, who sat in front of Display Console 1, had before him, in addition to the search controls and indicators previously described (Fig. 6), the display of the Sector Scan Indicator, plotting bearing deviation from the transducer beam axis against range. A second B-scan display was available for special receivers such as the Frequency Scanning Receiver or the Graphic Indicator.

A second operator observed the displays of Console 2 (Fig. 6). The upper of these was an A-scan which indicated amplitude versus range. The lower display was the electronic range recorder, which utilized the long persistence of a dark trace tube in a presentation of echo and background over periods up to one hour. The trace was a succession of horizontal lines, one for each ping, displaced vertically in a similar manner to the lines of a conventional range recorder. Echoes produced spot-darkening. Time integration over any number of pings was available. Erasure could be accomplished in 15 seconds.

Power Supply and Distribution

One 8-kva generator supplied power to the driver; another supplied power for all other electronic units. The d-c energy used by the final amplifier was stored mechanically in a flywheel mounted on a special motor-generator set. The 3-phase a-c output of this set was converted to high-voltage direct current in a conventional three-phase full-wave rectifier system. The duty cycle at maximum pulse energy was 1/30. Power controls and switches for the distribution of the power to all units of the system were located on central distribution panels.

A single 40-wire cable from a junction box on the main power-control panel was run to a distribution panel on the first rack. Short cables of the same type interconnected like distribution panels on all racks. All a-c power was distributed from these panels to the various components of the system.

RESEARCH AUXILIARIES

The equipment design took into consideration the provision of instrumentation for research as well as the establishment of equipment feasibility. Neither of these objectives

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is best served by a static installation such as an engineering model or prototype. Development extends beyond the laboratory into the field, and involves comparisons of different equipments and progressive improvements. Research requires special instrumentation which can be dispensed with in fleet equipment; among these are an arrangement of monitors and tape recorders. These auxiliaries are essential for research and experimentation but would not ordinarily be included in an operational sonar system.

Equipment Monitor

Measurements observed in underwater acoustics depend upon equipment characteristics, self-noise, target characteristics, and the nature of the medium - any one of which may change with time. While conducting performance research with a system, it is essential that these parameters be kept constant or be repeatedly measured quantitatively. In the long-range search system, instrumentation for their measurement was included as an integral part of the system. For full description see Ref. 4.

The equipment monitor consisted of a B-19-H hydrophone mounted topside in the same horizontal plane as the axis of the main sound beam when the transducer was not tilted, and a monitor console (Fig. 7) in the forward torpedo room containing circuits for the transmitting and receiving functions and the displays.

As a receiver the monitor received energy from the echo-ranging transducer and displayed the pulse power, pulse shape, pulse length, and the wave form of the individual cycles making up the transmitted pulse. The transducer beam pattern could be plotted by the monitor. Also the frequency of the echo-ranging driver oscillator could be measured directly.

As a transmitter, the monitor generated and transmitted various types of calibrated signals either through the water or directly to the input of the signal processors. A calibrated c-w signal was available for alignment of the echo-ranging receivers. Simulated echoes of known target strength and doppler shift were provided. A calibrated reference signal was generated for comparison with noise, reverberation, and echo levels. The receiving beam-pattern of the system's transducer could be recorded on a beam-pattern plotter.

The monitor facilitated the objective evaluation of the experimental sonar system, and made for economy of operational time and facilities by providing accurate checks on the system performance and by providing a means for measuring noise, reverberation, and echo levels.

Magnetic Tape Recording

The need for a means to store data for later analysis was recognized early in the program. To fill this need, a single channel magnetic tape recorder was installed as an integral part of the equipment monitor and was used to record the output of a narrow-band receiver. The output of the whole transducer was processed through this receiver where it was heterodyned to a frequency of 800 cycles before it was recorded.

As operations progressed, the need for recordings of high fidelity at the signal frequency was recognized. In the last three operating periods a high-quality recorder capable of recording on single or dual channels was installed. A tuning-fork-controlled a-c supply was used to stabilize the recorder drive motor. With this recorder, broad-band, single-channel recordings were made of the transducer output for complete

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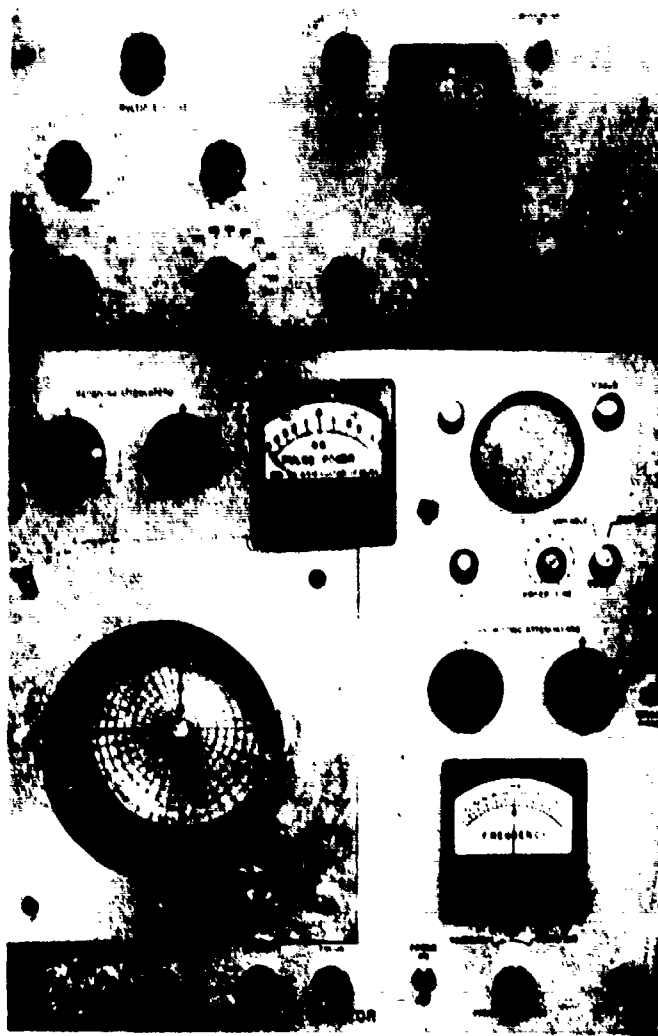


Figure 7 - Monitor console

echo-ranging cycles. Rectangular pulses both of c-w and of noise with bandwidths of 30, 100, 300, and 1000 cycles per second, and durations of 10, 30, 100, 300, and 1000 milliseconds were used. Recordings were also made of the outputs of the Frequency-Scanning and Time-Delay Receivers.

Two types of dual channel recordings were made. In one case the outputs of the right and left halves of the transducer were recorded directly at 10 kc using a 5-kc bandpass filter. These split transducer recordings are used in the Laboratory for signal analysis methods such as correlation and other statistical techniques. In another case, signals were recorded directly on one channel, and, to decrease the phase error introduced by the recorder signals, were also translated to a 500-cps center frequency, and recorded on the second channel of the dual-channel recorder.

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III - DATA

The preceding chapters described the early analysis which indicated that long ranges appeared obtainable by active sonar and then gave a detailed description of the equipment which would provide those ranges. This chapter tells the conditions under which the equipment was employed and presents the data which were obtained. For completeness, and for the purpose of identifying the oceanographic conditions, details of operations and operating conditions are listed.

The data obtained with the LRS equipment were taken to provide additional information about the factors which control the detection ranges, and to go beyond the determination of maximum detection ranges. The factors which were studied were propagation, target strength, self-noise, reverberation, and recognition differentials. Then, when all the data were assembled, it was apparent that some measure of the detection capabilities of the sonar could be obtained. This chapter summarizes these data, first taking up each factor in the order listed above.

After the test data were obtained, it was realized that the surface-bounded duct was the most commonly exploited acoustic path. Therefore, data on the probability of occurrence of such ducts are included.

PROGRAM OF OPERATIONS

The GUAVINA arrived in Key West, Florida on 1 February 1951. Operations began 5 February 1951 with the 10-kc equipment and continued through 28 March 1952. In this period a total of 140 operating days were realized. Operations were divided into seven phases, the first five of which were reported in Naval Research Laboratory letter reports (Refs. 7, 8, 9, 10, and 11). A summary of these operations is given in Table 2.

Most operations were carried out in the area between Key West and Cuba in water which varied in depth from 100 to 1000 fathoms. Two weeks of the third operating period were used for propagation studies and were conducted in deep water south of Cuba. Three weeks of the fourth operating period were spent in deep water near Bermuda and in the area between Bermuda and Halifax, Nova Scotia. This phase was on a time-sharing basis with the Variable Depth Sonar (VDS) installed in the escort ships, USS FRANCIS M. ROBINSON (EDE-220) and USS BLACKWOOD (DE-219). During the two final phases, water up to a depth of 2000 fathoms was obtained by operating west of Cuba and in the Gulf of Mexico.

Sea states encountered varied from state 0 to state 4. Water conditions were variable, but surface-bounded ducts varying in thickness from 50 to 250 feet were usually present in the Key West area. In the deep water areas of the Gulf of Mexico and the Caribbean, surface-bounded ducts 150 to 300 feet in thickness were common.

Controlled submarine targets were available for only eighteen days. The USS CHOPPER (SS-342) and the USS CUTLASS (SS-478) were used four days each for measurement of target strength. The USS CUBERA (SS-347) and the USS SEA CAT (SS-399) were

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TABLE 2
Program of Operation

Phase	Dates	Operating Days		Type of Operation	Targets	Area
		Total for Phase	With Controlled Submarine Target			
I	5 Feb-16 Mar 1951	29		Calibration Noise Measurements Echo Ranging	Salinan Sea Cat	Key West
II	9 Apr-18 May 1951	27		Echo Ranging Reverberation	Of Opportunity	Key West
III	11 June-17 July 1951	30		Echo Ranging Propagation Bottom Reflection	Albatross Sea Cat Wilkie	Key West Caribbean
IV	13 Aug-14 Sep 1951	15	4	Target Strength Echo Ranging Reverberation	Chopper Salinan Robinson Blackwood	Key West Bermuda North Atlantic
V	15 Oct-7 Dec 1951	20	5	T. D. Receiver Recording Signal Processing	Cubera Robinson Sarsfield Salinan	Key West Gulf of Mexico
VI	24 Jan-8 Feb 1952	5	4	10 and 7 kc High Power Target Strength	Albatross Cutlass	Key West Gulf of Mexico
VII	3 Mar-28 Mar 1952	14	5	Freq. Scan Rec. Echo Ranging Recording	Sea Cat	Key West Gulf of Mexico
Totals		140	18			

available five days each as targets for tests of special receiving equipment. The remaining submarine time of ten days was on a "not-to-interfere" basis, when the target submarine was operating in the same or an adjacent area.

In the first three phases, targets of opportunity were frequently used for echo-ranging tests. The USS SEA CAT (SS-399) and the USS SALINAN (ATF-16) working on another project were usually assigned the same or adjacent operating areas, and were also used as echo-ranging targets. The USS ALBATROSS (AMS-1), with a target simulator installed on it, accompanied the GUAVINA on a trip around Cuba and assisted with propagation measurements.

In view of the great number of high priority tests requiring submarine time, it was necessary and deemed advantageous to sacrifice a part of the program in order to obtain continuous service of a target submarine. Operational research involving sweep procedures and determination of lateral ranges and glimpse probabilities was relinquished.

PROPAGATION

The propagation loss term constitutes a very important element in the echo-ranging equation. In Chapter I, four acoustic paths were listed, and in this section, attention will

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be centered on propagation along two paths; the surface-bounded duct and the path which involves reflection from the bottom. Propagation measurements were taken under many conditions with both submarine and surface ship targets.

Propagation measurements were taken in all the operating periods except the initial two. The dates and locations of operations are listed in Table 2. The observations were made in water varying in depth from 100 fathoms off Key West to 2400 fathoms south of Cuba and off Yucatan. Targets were live submarines, surface ships such as the ALBATROSS, and synthetic targets or transponders. Ranges varied from 500 yards to 40 kys. Sea states encountered varied from flat calm to sea state 3. Few data were taken at higher sea states. Although no actual count was made, the number of pings observed and measured were of the order of tens of thousands. Some results of these measurements were reported in Refs. 12, 13, 14, and 15. The results yielded information on absorption, leakage coefficients, and on bottom-reflection loss.

The round trip propagation loss in db is the difference between the intensity of the outgoing ping and the received echo plus the target strength as brought out in Eq. (3).

$$I_1 - I_e = 2L - T \quad (3)$$

where

I_e = the intensity of the echo in db at the transducer face

L = one-way transition loss in db

I_1 and T have the same meaning as in Chapter I.

Instrumentation described in Chapter II enabled direct measurement of I_1 and I_e , and recording for later analysis. By varying the transducer tilt (inclination to the horizontal) from 0° to 30° , observations could be made of transmissions in ducts, and by way of the bottom-reflected path. On several occasions, sufficient power was transmitted by a side-lobe to permit simultaneous propagation via the surface duct, and via bottom-reflected paths.

The observed losses in ducts can be accounted for by three terms: (a) calculable divergence loss, L_D ; (b) an absorption loss, $L_0 = \alpha_0 R$ where the coefficient α_0 is measurable in the Laboratory; and (c) a third loss, $L_L = \alpha_L R$ ascribed to leakage out of the duct. In equation form

$$L = L_D + L_0 + L_L \quad (4)$$

These will be discussed in order.

The power contained between the angle of radiation of the limit ray of the rays trapped and an equal angle above the horizontal, diverges in a vertical plane until it fills the duct and thereafter experiences no further divergence in this plane. It will be shown in Chapter IV that the divergence loss is equivalent to that of spherical divergence to half the distance to the first tangency of the limit ray with the bottom of the duct, and thereafter to that of cylindrical divergence minus three decibels. Within the accuracy of present measurements, except where otherwise noted, spherical divergence to a range of 1000 yds may be assumed, leading to the mathematical expression

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$$\begin{aligned} L_D &= 20 \log 1000 + 10 \log \frac{r}{1000} - 3 \\ &= 57 + 10 \log R \end{aligned} \quad (5)$$

where r is range in yards, R is range in kiloyards, and L_D is divergence loss.

From range 1 to range 2, both in excess of 1000 yards,

$$L_D = 10 \log R_2/R_1 \quad (6)$$

The latest summary of studies in sound absorption in sea water is given by Ref. 16. Figure 8, taken from Ref. 16, gives the best available data on sound absorption in

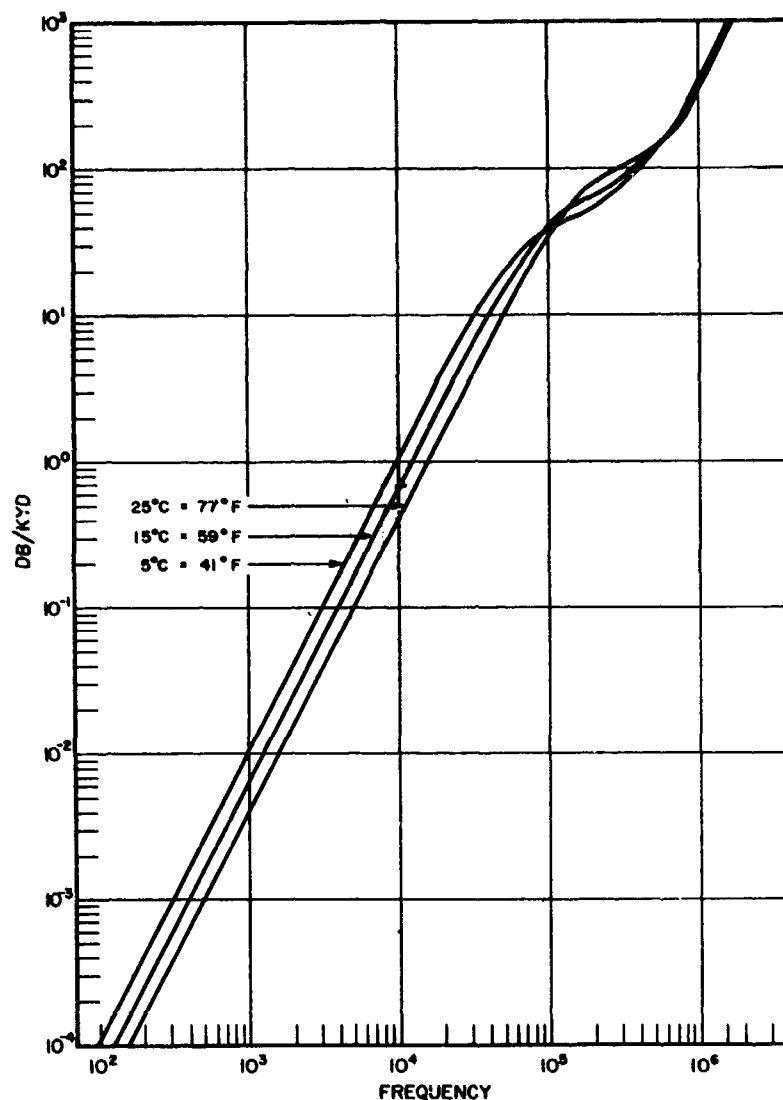


Figure 8 - Sound absorption in sea water

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sea water. The absorption coefficient was found to be dependent on temperature and salinity as well as frequency, and its value for 10-kc sound in sea water, 35 parts per 1000 salinity, at a temperature of 15°C, is 0.42 db/kyd. If temperature t is measured in degrees Fahrenheit, an approximate formula for absorption coefficient is

$$\alpha_0 = \frac{28}{t} \quad (7)$$

Measurement of I_i and I_e and the assumption of a target strength enable computing loss L by the use of Eq. (3). Then substituting this L and computed values of L_D and L_0 into Eq. (4), L_L can be solved for and α_L obtained. The leakage coefficient, α_L , was found to depend on sea state, duct thickness and frequency. Figure 9 is a plot of α_L , the leakage coefficient, versus duct thickness for 10-kc sound in sea states from 0 to 6 in an isothermal, surface-bounded duct. There is little actual data for the higher sea states, but the curves for sea states 1 through 3 are based on many measurements made with the 10-kc system and on other field experiments.

A very slight negative temperature gradient in the channel is beneficial according to the theory developed in the next chapter. While observation of the very small negative gradients which lead to lower propagation loss is difficult with the resolution afforded by present bathythermograms; nevertheless, on occasions of optimum water conditions, a search for such gradients has sometimes been successful.

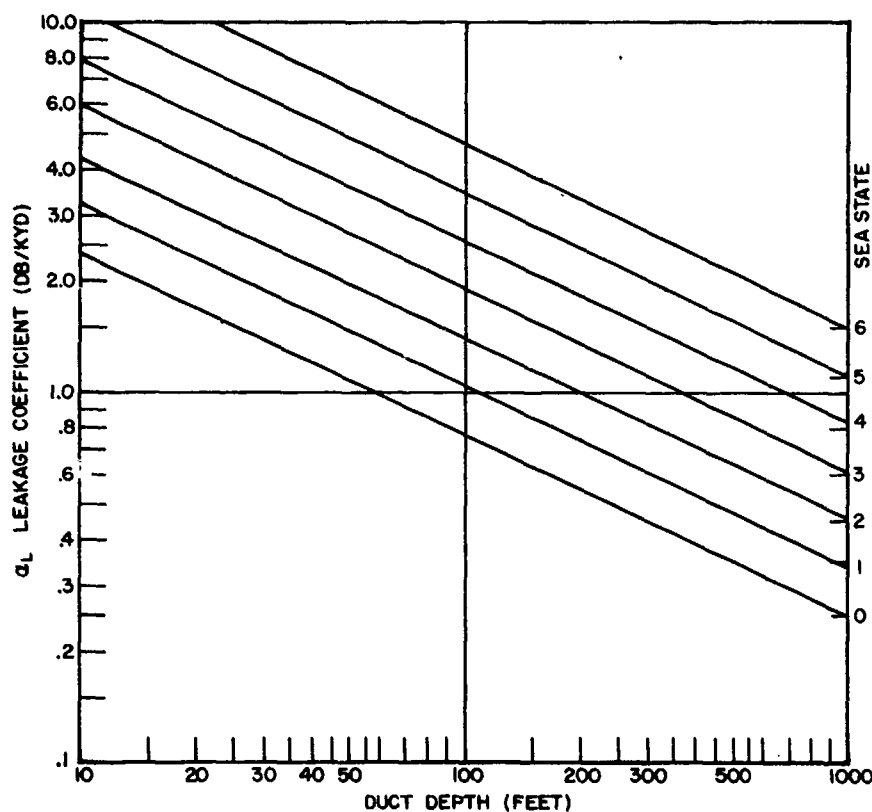


Figure 9 - Coefficient of leakage out of ducts

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Losses at bottom reflection were found to vary from 0 to 21 db at 10 kc, depending on location, character of bottom, and grazing angle. The lowest loss at reflection was observed in shallow water off Key West. In this situation, there was a sharp negative gradient of -14* per hundred feet. Despite the fact that the transducer was not tilted, echoes were observed on targets up to 8 kyds away. The only plausible explanation appears to be paths involving reflection from the bottom. The reflection loss must have been low in this case at the maximum range.

The highest values (21 db) were also obtained off Key West in shallow water with the transducer tilted down at 30°. For deep water, smooth bottom, and grazing angles up to 30°, the most commonly observed value was 11 db. During the third operating period, 11 db was observed repeatedly in about 300 pings. More work must be done on this subject, before characteristic values of bottom-reflection losses can be given.

Interpretation of the data here discussed will be given in more detail in Chapter IV.

TARGET STRENGTH

A second item of significance in the echo-ranging equation is the target strength. The target strength of several guppy submarines was measured at 10 and at 7 kc. These measurements were made during the fourth and sixth operating periods, on the following dates:

Aug. 13-15, 1951

Feb. 4-8, 1952

Feb. 26-28, 1952

In the August 1951 tests, observations were made in the Key West area in water 100-400 fathoms deep with the USS CHOPPER (SS-342) as the target. The measurements were made at 10 kc with the USS GUAVINA, the measuring vessel, circling at approximately 1000 yards. In the tests early in February 1952, the target strength of the USS CUTLASS (SS-341) was measured both at 10 kc and at 7 kc. These measurements were made in deep water. At a frequency of 10 kc, the range between target and measuring vessel covered the interval 1 to 12 kyd; at 7 kc the ranges were 1 and 2 kyd. The tests on 26-28 February 1952 were made with the USS CHIVO (SS-478) as the target; the measurements were made in the Key West area in about 150 fathoms of water; the frequencies used were both 7 kc and 10 kc; the range was about 1 kyd. Details of the work on the CHOPPER are described in Ref. 17 and 18. Descriptions of the tests in 1952 are given in Ref. 19.

Two methods of obtaining target strength are given in detail in Ref. 17. The standard method assumes that the transmission loss to and from the target, $2L$ can be calculated; the measured quantities are the intensities of the transmitted and returned signals, I_1 and I_e respectively. Inserting these quantities into the equation $2L - T = I_1 - I_e$, the target strength T can be computed. The loss is computed as spherical divergence of 60 db minus a surface-reflection gain of 3 db plus 1 db attenuation.

In the comparison method, no assumption regarding transmission loss is required. The installation of an echo-repeater on the target vessel plus two accurate measurements of intensity differences suffice to give the target strength. On the target ship, the quantity measured was the difference in intensity between the received signal and of the outgoing ping of the echo-repeater (reduced to one yard from the transducer). On the observing vessel, the quantity measured is the difference in intensity between true echo

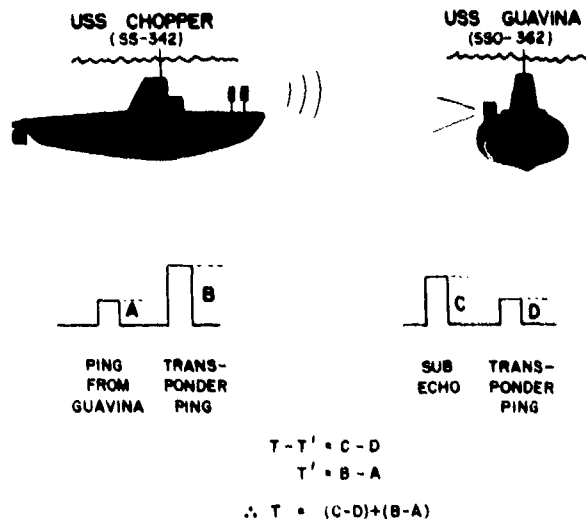
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Figure 10 - Comparison method of target strength determination

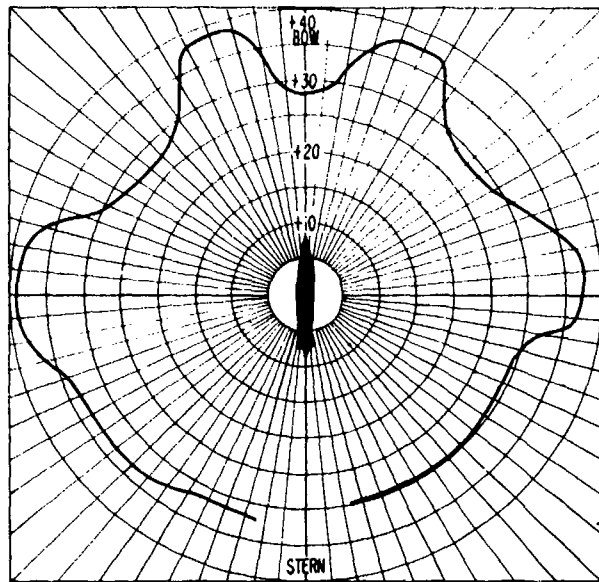


Figure 11 - 10-kc target strength of guppy submarine

about 30 db; in shallow water, 22 db. This difference has not yet been accounted for.

There was no significant difference in target strength when measured by means of an acoustic beam aimed normally at the submarine and travelling via a surface-bounded duct; or, when measured by means of a beam emitted at a depression angle of 30° and propagated via bottom reflection, which reached the underside of the target, striking it at an angle of 30°. Target strength as measured by way of the bottom-reflected paths is based on fewer than 100 echoes. Hence, caution must be exercised in drawing conclusions.

and the signal from the transponder (Fig. 10). From these two quantities, the target strength can be computed. It is, of course, assumed that the transmission losses in the two directions are equal. In essence the target strength of the submarine is determined by comparing the echo with a return from an echo-repeater of known target strength.

The measurements on the CHOPPER were the most complete. Over 1000 pings were observed and measured. The average target strength was 32.7 db, and its dependence on azimuthal aspect is shown in Fig. 11 taken from Ref. 17.

The results obtained during the sixth operating period, with the CUT-LASS and CHIVO as targets, supply supporting information to the above. Due to problems arising from equipment performance which had not yet been resolved, the output intensity and the directivity of the LRS system were both lower than anticipated. As a consequence, the number of returned echoes was reduced. Nevertheless, significant observations were obtained, which are presented in Tables 3 and 4.

Included in this work were some measurements at 7 kc. The observations indicated no material differences between 7-kc and 10-kc target strength, and details are given in Ref. 19.

Later measurements performed in June 1953 off New London, and as yet unreported, indicated no dependence of target strength on frequency. About 2,000 pings were observed and measured; the target was the USS DOGFISH (SS-350), a guppy submarine. In deep water the target strength seemed to be

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TABLE 3
Target Strength of USS CUTLASS (SS-341)
10 kc

Aspect	Comparison Method		Standard Method	
	T*	N*	T†	N
10 ± 10° 350	10.8 db	14	12.4 db	14
30 ± 10° 330	14.8	12	18.3	12
50 ± 10° 310	20.7	13	21.1	13
70 ± 10° 290	24.0	11	22.8	12
90 ± 10° 270	30.6	11	27.3	9
110 ± 10° 250	24.1	13	21	13
130 ± 10° 230	16.6	93	16.5	95
150 ± 10° 210	17.6	12	12.3	12
170 ± 10° 190	13.7	9	10.6	10

*T = Target strength in db

N = Number of pings or echo-ranging attempts
in each group

†The target strength as measured by the standard
method reduced by 6 db to take into account the
multiple paths arising from surface reflection.

Measurements were made utilizing signals travelling over four different acoustic
paths:

- (1) direct - direct
- (2) direct - bottom
- (3) bottom - direct
- (4) bottom - bottom

The term "direct" indicates that the signal travelled via the surface-bounded duct.
The term "bottom" indicates that the signal travelled via reflection from the bottom.
The first term describes the path of the outgoing signal, while the second describes the
path of the returned signal.

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TABLE 4
Target Strength USS CHIVO (SS-478)
All Aspects
10 kc

Aspect	Comparison Method			Standard Method		
	T*	SD*	N*	T	SD	N
10 ± 10° 350	12.0 db	8.5 db	85	13.5 db	5.5 db	85
30 ± 10° 330	15.5	8.5	104	16.0	5.5	114
50 ± 10° 310	21.5	8.5	75	19.5	5.5	77
70 ± 10° 290	28.0	8.5	67	23.0	5.5	67
90 ± 10° 270	32.0	8.5	207	26.0	5.5	225
110 ± 10° 250	23.5	8.5	98	18.0	5.5	98
130 ± 10° 230	16.0	8.5	78	14.0	5.5	78
150 ± 10° 210	18.0	8.5	94	14.5	5.5	94
190 ± 10° 190	18.0	8.5	81	9.5	5.5	81

*T = Target strength in db

SD = Standard deviation in db

N = Number of pings or echo-ranging attempts in each group

Table 5, taken from Ref. 18 shows the absence of significant variation of target strength when observed with signal travelling over the four different paths.

TABLE 5
Effect on Target Strength of Incident Angle in a Vertical Plane
10 kc

Echo	Standard Method		Comparison Method	
	Target Strength	Standard Dev.	Target Strength	Standard Dev.
Direct-Direct	33.9 db	3.7 db	34.9 db	4.5 db
Bottom-Bottom	35.9	4.1	35.4	6.7
Direct-Bottom or Bottom-Direct	35.5	3.9	37.5	5.6

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From the foregoing discussion and data it may be inferred that in operational analysis a 10-kc target strength for guppy submarines of 20 db rather than the conventional 10 db should be used in the echo-ranging equation. This 20-db number is considered a conservative average value of target strength at all aspects.

The dependence of 10-kc target strength of guppy submarines on azimuthal aspect is indicated in Fig. 11. No dependence on vertical aspect was found.

BACKGROUND INTERFERENCE

The unwanted signals against which echoes must be identified, have been variously designated as the interfering background, background noise, or simply, noise. The components of the interfering background are target noise, ambient noise, self noise, and reverberation; and these components are often grouped into two categories, noise and reverberation. The background noise may consist of one or more of these components, but usually one of them is dominant.

The magnitude of the background interference constitutes an important term in the echo-ranging equation, along with transmission losses and target strength. This section is devoted to a discussion of the data obtained which relate to noise and reverberation.

Noise

Target noise is disregarded because whenever it obscures the echo, there is no need to echo-range in order to detect a submarine—passive sonar will suffice. Ambient noise provided no observable interference with echoes during this program. Self-noise and reverberation were found to be interfering under different conditions; with reverberation dying out at long ranges and seldom if ever limiting echo ranges.

The self-noise measurements of the 10-kc LRS mounted on the GUAVINA are presented in Fig. 12. These data show the non-directional self-noise in a one-cycle band, observed at three speeds of the vehicle and at periscope depth.

1.9 knots	45 rpm
2.7 knots	60 rpm
5.1 knots	125 rpm

The deep sea ambient noise for sea state 2, is also drawn in Fig. 12. All plotted data were reduced to spectral level.

Reverberations

Observations - The reverberations were observed all through the LRS program particularly at the times and places where propagation and target strength measurements were taken. The observations were recorded on magnetic tapes, which were later analyzed in the Laboratory. The outgoing pings consisted of 10-kc sine waves, and noise of various bandwidths centered at 10 kc. Ping lengths were 10, 100, and 1000 ms.

Methods of Analysis of Recordings - Two methods of analysis of these recordings were used, both of which gave results which are consistent with each other. In one method, the recordings were played back through a power-level recorder which made a

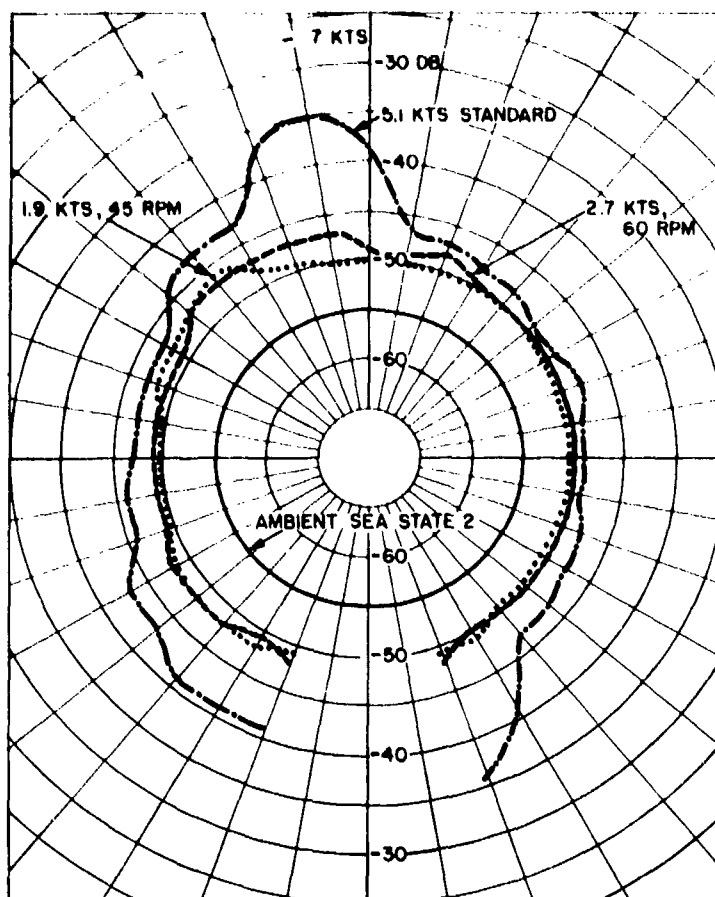


Figure 12 - LRS self-noise

written trace. Ten pings in each situation were analyzed. The amplitude was noted at points on the trace corresponding to a range difference of one or two kiloyards, and the intensity relative to an arbitrary reference level was observed. Averages of these intensities were obtained and the reverberation decay curves were then plotted. In the second method, the tape recordings were fed into a CRO and the traces were photographed. The traces of ten to twelve pings were superimposed by successively photographing them on a single exposure. The CRO had two sweep rates: the fast sweep permitted a detailed analysis of the first two kiloyards; the slow sweep enabled the experimenter to analyze up to 25 kiloyards on a single sweep.

A mean of the superimposed traces was observed and measured, and a decay curve was computed from these measurements. The decay curves, obtained by these two methods are consistent with each other, as is shown in Figs. 13, 14, 15, and 16.

For the initial kiloyard the decay curves are consistent with -9 decibels per distance doubled (db/dd) or $-30 \log R/R_0$ (where R is the range and R_0 is the initial measuring point in kiloyards). For longer distances, the curves are consistent with the expression

$$- \left(10 \log \frac{R}{R_0} \right) + 2(\alpha_0 + \alpha_k) (R - R_0)$$

α_0 = absorption in db/kyd

R = range in kiloyards

R_0 = initial measuring point (in kyds)

α_k = may be considered an attenuation, a leakage coefficient out of the channel, or simply a residual attenuation coefficient

Figures 17, 18 and 19 are plots of α_k for three cases.

Signal-to-Reverberation Ratio - Observations of signal-to-reverberation ratio with the target in a surface-bounded duct at ranges of 10 to 34 kiloyards indicate that on the average the echo intensity exceeds the reverberation intensity by 14 db \pm 3 db throughout this range interval, with 0.5-sec pulses. The theory discussed in the next chapter shows that the excess of signal-to-reverberation intensity should fall by 3 db per distance doubled. The theory would be satisfied if 17 db at 10 kyd and 12 db at 34 kyd were the observed values, and these figures do fall within the limits of accuracy of the observations. At 41 kyd, the LRS in conjunction with the Frequency Scanning Receiver showed a substantial excess of signal-to-reverberation intensity, although a lesser accuracy will have to be attached to this observation than to those made at shorter ranges.

Pulse Length - Attempts to demonstrate compatibility with theory as far as pulse length was concerned were not immediately successful, although there was an indication that the trend was toward higher reverberation intensities at longer pulse lengths. In view of the lack of reverberation limitations even with the longest pulses used, the importance of pinning down the relationship between theory and experiment is reduced for this particular problem.

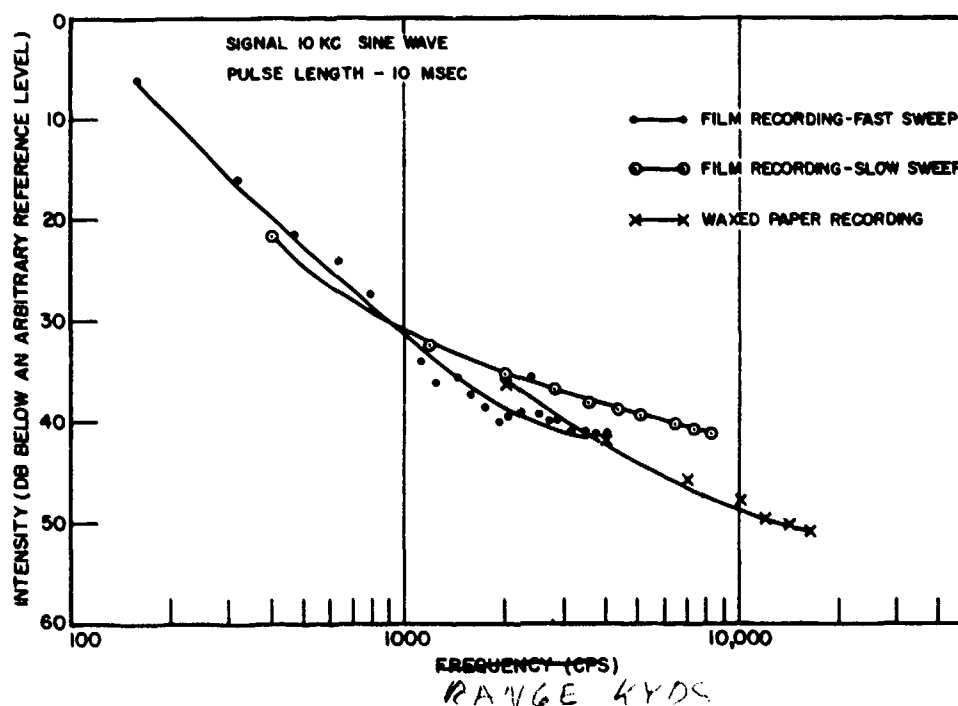


Figure 13 - Ten kilocycles reverberation decay

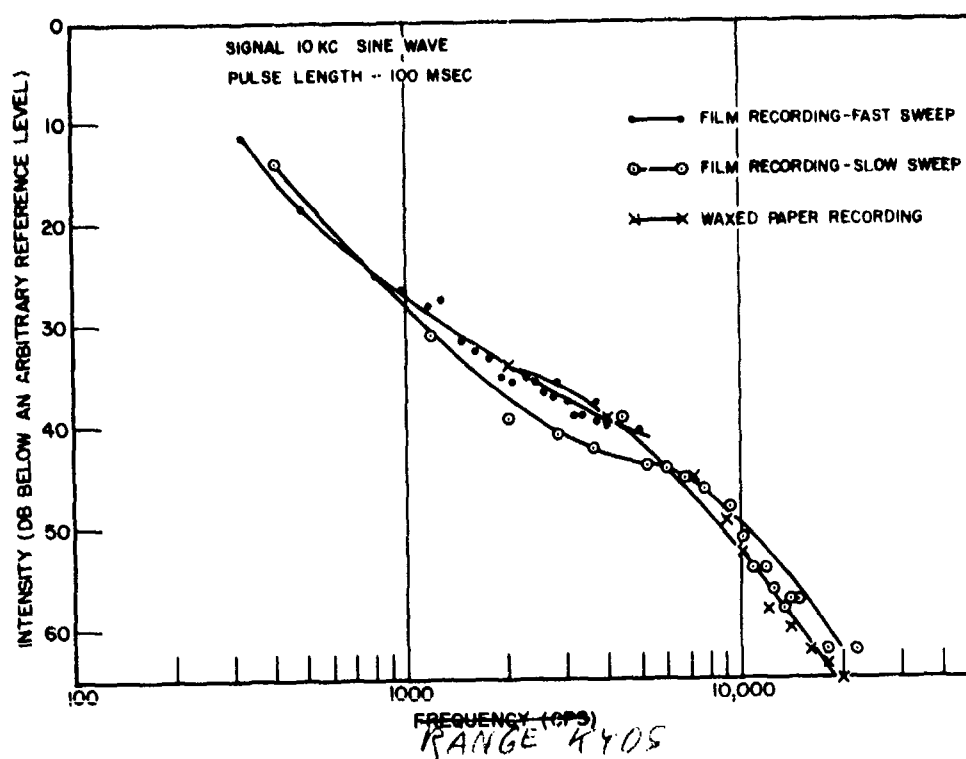
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Figure 14 - Ten kilocycles reverberation decay

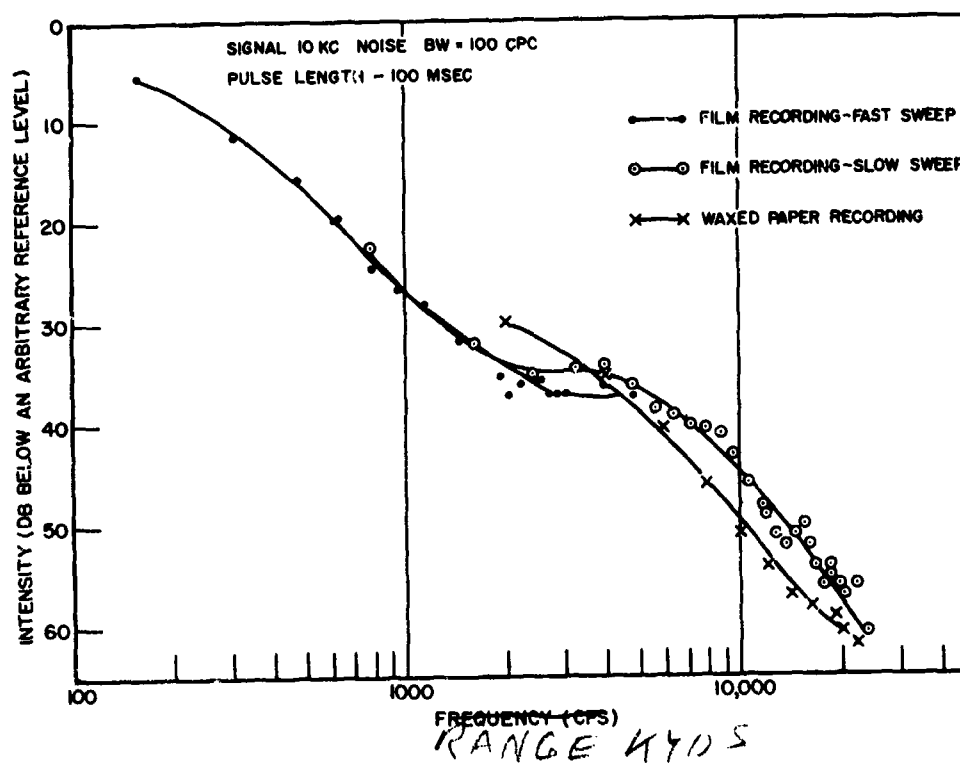


Figure 15 - Ten kilocycles reverberation decay

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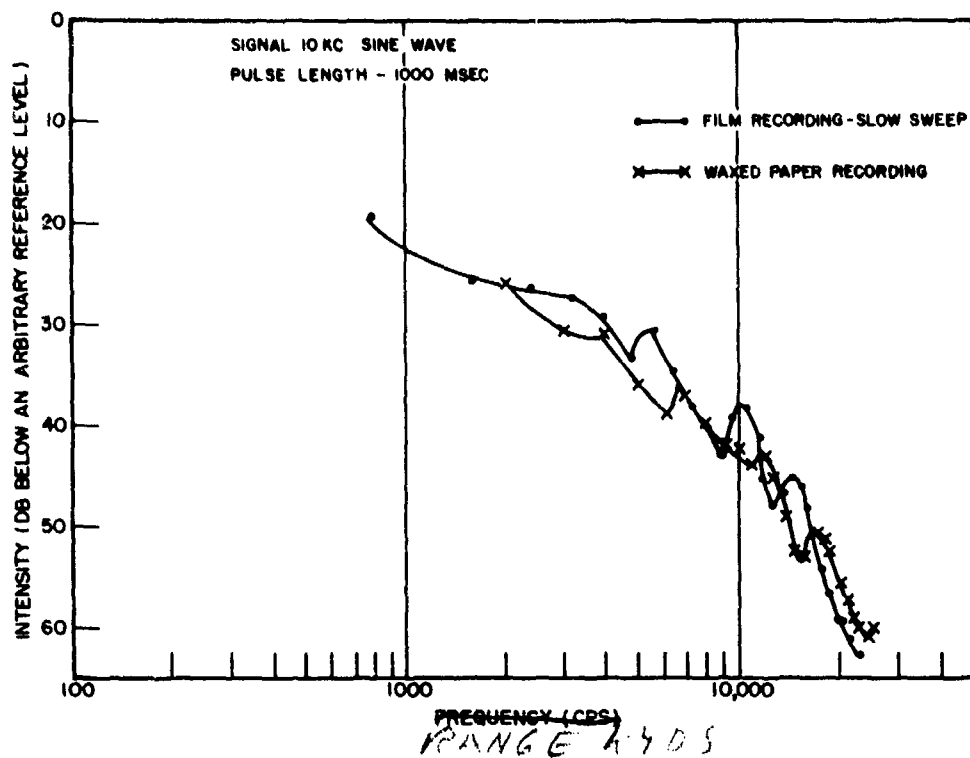


Figure 16 - Ten kilocycles reverberation decay

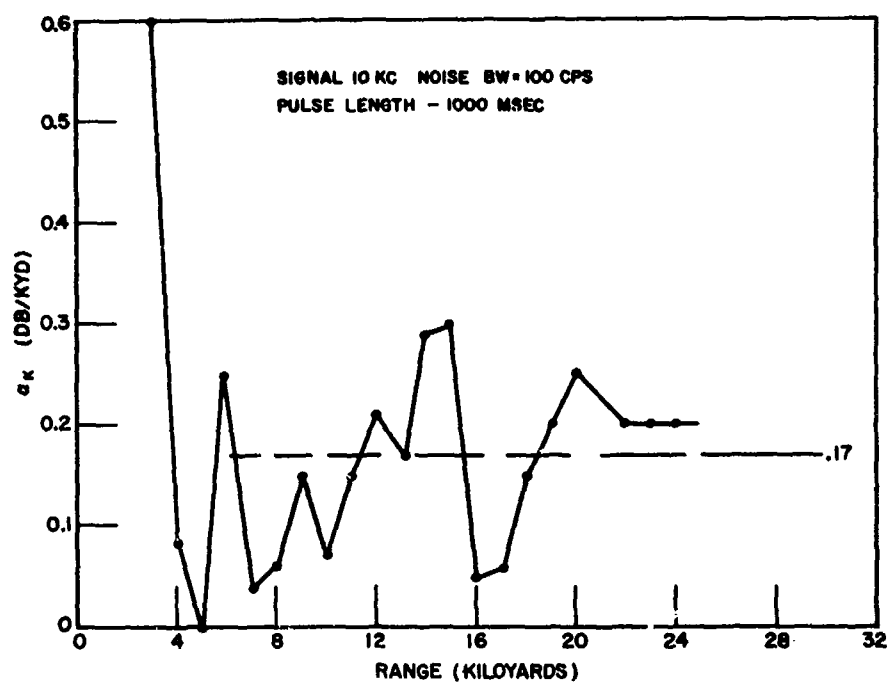


Figure 17 - Reverberation leakage coefficient

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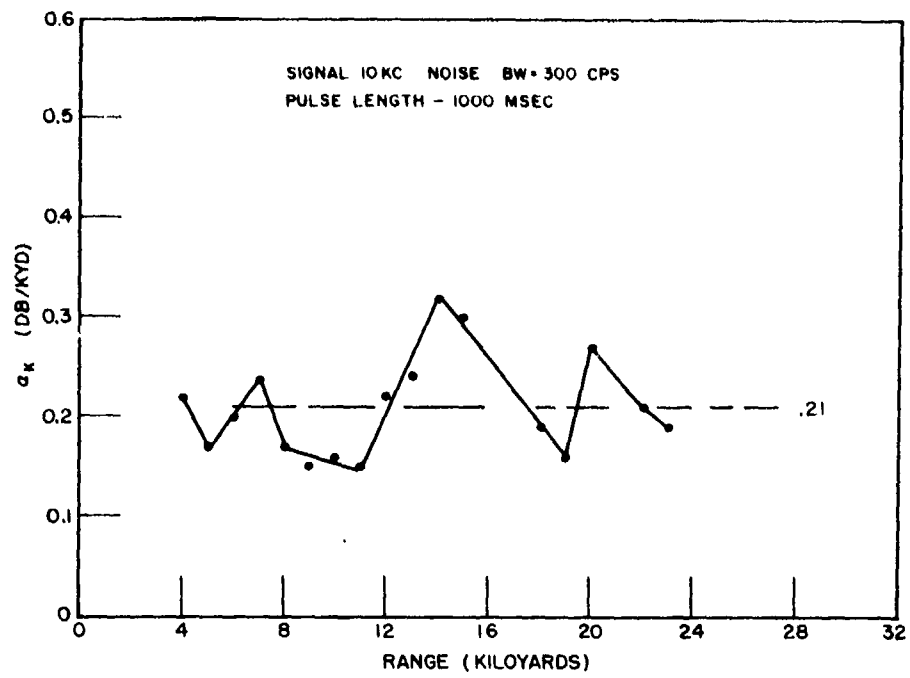
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Figure 18 - Reverberation leakage coefficient

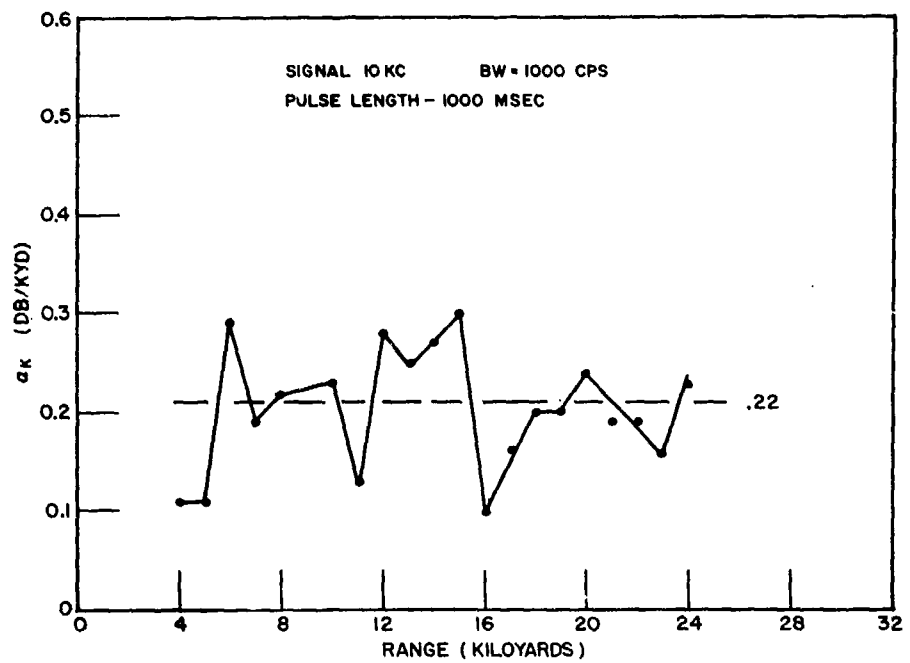


Figure 19 - Reverberation leakage coefficient

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RECOGNITION DIFFERENTIALS

Two special devices for signal processing were described in Chapter II, the Frequency Scanning Receiver and the Time Delay Receiver. These equipments are designed to improve recognition differentials.

It was not possible to make direct measurements of the recognition differential. However, comparative measurements were made simultaneously with the LRS using a conventional receiver and the LRS using each of the two special devices. These comparative measurements provided the basis for the conclusion that the special devices gave improved recognition differentials over conventional receivers.

Figure 20 - taken from Ref. 6 - contains photographs of the FSR display. Figure 20a is a photograph of an echo of a submarine target at a range of 17,000 yards. The displacement of the echo to the left of the reverberation indicates down-doppler of about 11-knots. Figure 20b illustrates the display of up-doppler, where the target is closing at the rate of 6 knots. While at first glance one might conclude that the echo would be completely obscured were it not for the doppler shift, experience indicates otherwise. If the gain were reduced till reverberation no longer appeared, the echo might still come in.

Comparisons between aural detection techniques using the LRS receiver and visual detection techniques of the Frequency Scanning Receiver were made during evaluation

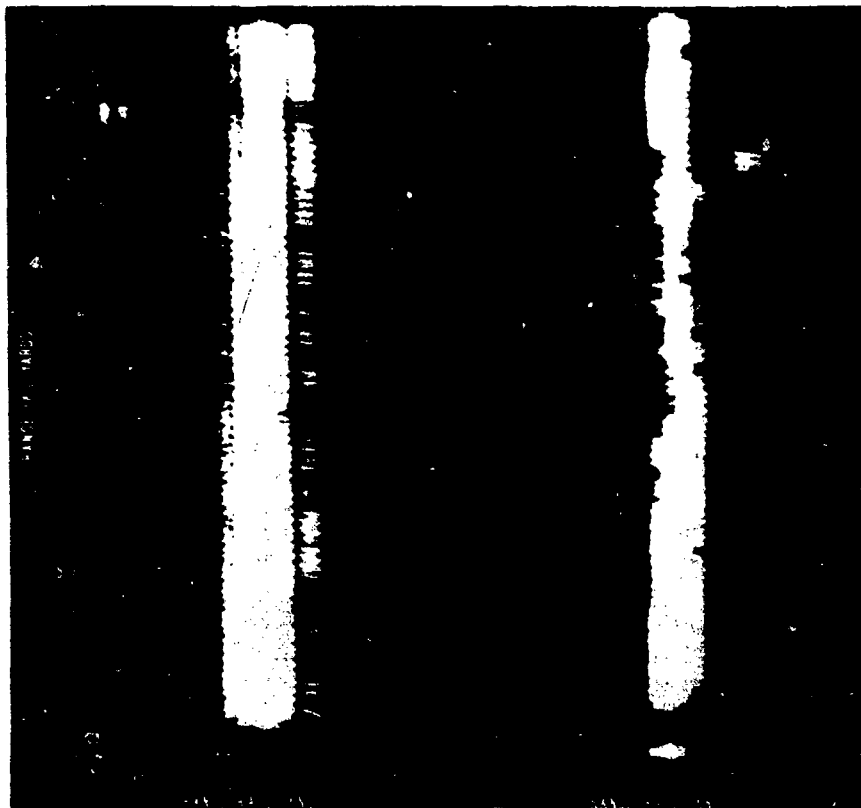


Figure 20 - Visual display of the Frequency Scanning Receiver

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tests of the 10-kc equipment in March 1952. These tests confirmed earlier results obtained at 20 kc in October 1950. With two aural operators manning an LRS sonar receiver having a bandwidth of 250 cps, and two operators viewing the FSR, relative detection efficiencies could be measured. During one run, the target submarine, USS CHIVO (SS-341), was making 9 knots on a diverging course at an average range of 15,000 yards. As shown in Fig. 21, the visual operators reported detection 50 percent of the

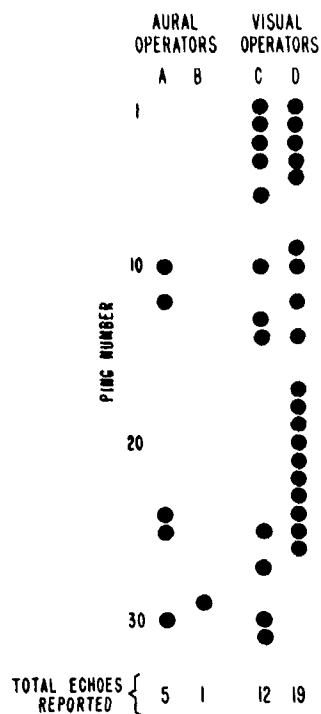


Figure 21 - Relative efficiency of aural detection with LRS receiver and visual detection with Frequency Scanning Receiver as measured during a 32-ping run

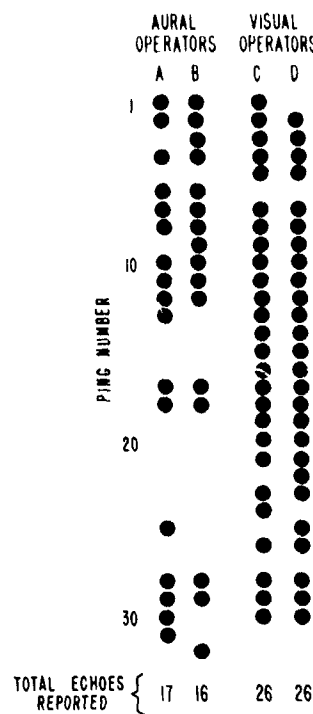


Figure 22 - Comparative results LRS and FSR displays, target range 20,000 yards

time, while the aural observers heard echoes in very few of the cases. On another run, at a range of 20,000 yards, where the aural detection was approximately 50 percent, the visual operators were able to detect echoes in 81 percent of the cases. These data are tabulated in Fig. 22.

In a test to determine the maximum range at which contact could be maintained, the aural observers reported loss of contact at 34,000 yards, while the FSR operators continued to report echoes out to 41,000 yards before contact was lost. Inserting these values of range into the echo-ranging equation and taking a value of 20 db for target strength, the equation yields an approximate value for the recognition differential of the FSR of 13 db. This value agrees favorably with the computed value for 300 ms. pulses, based on the ratio of filter bandwidth employed to the critical bandwidth of the ear. In the case of noise-masked echoes, then, it is believed that an improvement of 5 to 7 db can be realized over conventional aural methods by using Frequency Scanning Receiver.

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The recognition differential relative to reverberation has not been determined experimentally for the FSR, but the selectivity of the filters is such that the recognition differential should improve at the rate of 5.8 db per knot of range-rate for low values of range-rate. At zero target doppler, the FSR should prove superior to the ear for dopplers of 7 cps or more. For a down doppler corresponding to a 2-knot range rate, the improvement is estimated at 6 db and, for an up doppler corresponding to a 2-knot range-rate, 8 db.

Figures 23 and 24 are photographs of the TDR display. Figure 23 shows the result of noise generated by the bow-planes of the echo-ranging submarine during the arrival of an echo. The horizontal echo pattern is easily distinguishable, even though several of the individual echo pulses are masked by the noise. Figure 24 is a photograph of the echoes obtained with the USS SEA CAT (SS-399) as the target (see Ref. 6) at 3 different ranges.

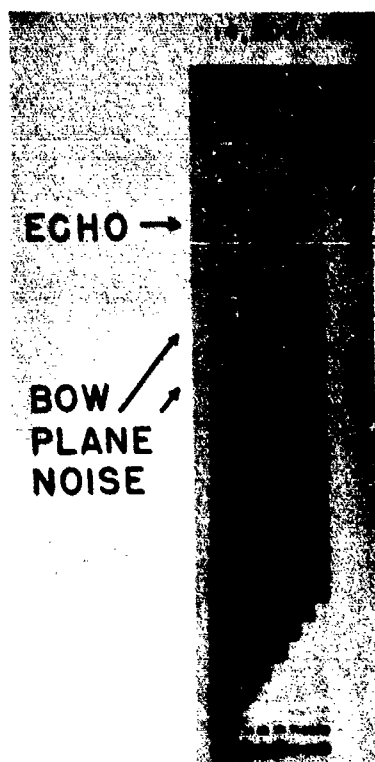


Figure 23 - Display of Time Delay Receiver (echo and noise)

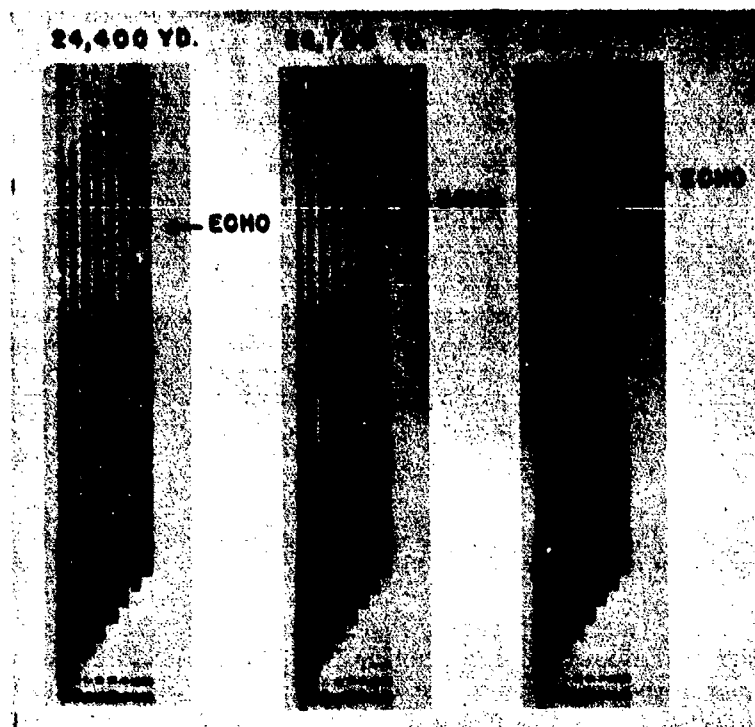


Figure 24 - Display of Time Delay Receiver echoes from submarine. Target at long ranges.

In the case of the Time Delay Receiver using methods of comparison in which visual observers viewed the chemical recorder display while aural observers monitored a single channel of the Selective Time Delay Receiver, data were obtained during field tests conducted in October and November 1951. On one test run in which the target submarine USS COBBLER (SS-344) maneuvered at a range of 23,000 yards, the visual operators detected echoes following nearly half of the pings, while the aural observers reported echoes in only 17 percent of the cases. Using a surface target, USS SALINAN (ATF-161) at a range of 15,000 yards, the aural observers averaged about 50 percent detection while the operators of the Selective Time Delay Receiver reported contact in 88 percent of the cases. Data from these runs are presented in Figures 25 and 26.

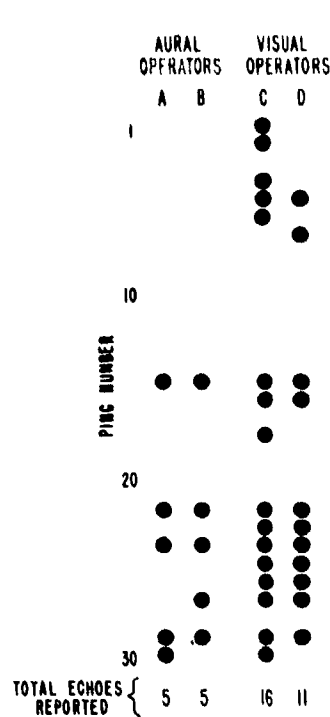
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Figure 25 - Relative efficiency of aural detection with LRS receiver and visual detection with Time Delay Receiver

(Run No. 5)

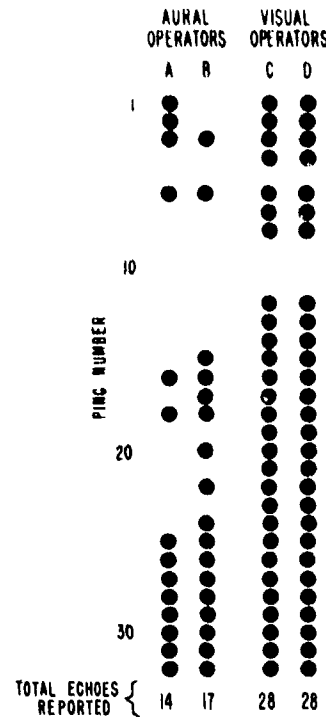


Figure 26 - Relative efficiency of aural detection with LRS receiver and visual detection with Time Delay Receiver

(Run No. 8)

During a maximum range run, contact was maintained with USS SEA CAT (SS-399) out to 28,000 yards, (see Fig. 24).

The field tests performed with the Selective Time Delay Receiver were accomplished with pulse powers of approximately 250 acoustic watts, about 9 db less than the power used in the majority of the LRS tests. The difficulty of evaluating the complex psychophysical factors involved in interpreting the visual display makes it impractical to assign a value to the recognition differential for this system. It is significant to report that the field evaluation studies show that the Selective Time Delay Receiver is definitely superior to conventional sonar systems employing aural detection, and that, for early target acquisition, it is equally as useful as the Frequency Scanning Receiver.

DETECTION CAPABILITIES IN SURFACE-BOUNDED DUCTS

The data accumulated for purposes reported in the preceding chapters, consisting of tens of thousands of pings, permit an estimate of the detection capabilities of the subject sonar. The observations confirm the prediction of the preliminary analysis that when surface-bounded ducts exist, long ranges are possible. While a preferable way of determining the detection capabilities of a sonar are by operational procedures, these are not available. However, the accumulated data permit an alternative if somewhat less rigorous method of obtaining a measure of the detection ranges of the gear.

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For purposes of analyzing these data, a "detection observation" is defined as that representative echo selected from a succession of echoes obtained on a single target in one location during a continuous time interval. The range associated with that observation was the maximum range observed during the succession of echoes. All told, 113 distinct "detection observations" were made in various water conditions, (such as temperature gradients, duct thickness, and water depth) and under varying degrees of equipment efficiency. Of these, eighty-one detection observations were made under water conditions which contained surface-bounded ducts. In many, if not most cases, the measurements were made for purposes other than maximum range determination; and the target was at some fixed distance from the transducer. In some cases, measurements ceased because the target ran out of the working area. In addition, measurements were made on targets of opportunity, when a target appeared at a convenient location at a convenient time. In general these range observations were not made at the longest possible ranges in the sense of "lost contact" ranges.

The detection observations in ducts are listed in Tables 6, 7, and 8. Table 6 gives the pertinent data on submarine targets in acoustic ducts. Tables 7 and 8 give the comparable data on surface ship targets; the former on targets deliberately located by the experimenters, the latter on targets of opportunity.

TABLE 6
Echo-Ranging Detection Observations on Submarine Targets

Target	Range	Date	Time
Sea Cat	12 kyd	2 March 1951	1000
Sea Cat	10	5 March 1951	0845
Sea Cat	20	8 March 1951	0930
Sea Cat	13	13 March 1951	0645
Sea Cat	15	14 March 1951	0900
Corporal	20	15 March 1951	0915
Surfaced Guppy	9	14 June 1951	0930
Sea Cat	8	16 July 1951	1130
Unidentified S/M	12	18 October 1951	1600
Cobbler	23	19 October 1951	1247
Cobbler	18	19 October 1951	1405
Cobbler	20	19 October 1951	1510
Cobbler	17.5	25 October 1951	1130
Chopper	18	25 October 1951	1458
Sea Cat	20	30 October 1951	1400
Sea Cat	20	30 October 1951	1727
Sea Cat	28	31 October 1951	1820
Sea Cat	24	1 November 1951	1624
Sea Cat	16	2 November 1951	0953
Cutlass	10	8 February 1952	
Chivo	13.3	10 March 1952	1558
Chivo	19	10 March 1952	1816
Chivo	20	11 March 1952	1401
Chivo	41	11 March 1952	1644
Chivo	11	12 March 1952	1115
Chivo	15.5	13 March 1952	1016
Chivo	13.8	13 March 1952	1128
Chivo	22.5	13 March 1952	1800
Chivo	22	14 March 1952	0923
Chivo	34.6	14 March 1952	1014
Sea Poacher	8.2	25 March 1952	1405
Sea Poacher	15	27 March 1952	1100
Unidentified Submerged Object	13	28 March 1952	

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TABLE 7
Echo-Ranging Detection Observations on
Surface Ship Targets
Targets Placed by Experimenters

Target	Range	Date	Time
Robinson	8 kyd	2 March 1951	1000
Robinson	10	5 March 1951	0845
Salinan	20	8 March 1951	0930
Salinan	15	14 March 1951	0900
Tuscarora	17.5	15 March 1951	0915
Salinan	8.5	19 April 1951	0920
Salinan	10	19 April 1951	1515
Robinson	10	20 April 1951	0920
Salinan	10	3 May 1951	0700
Tuscarora	8	20 June 1951	0900
Wilkie	9	25 June 1951	1200
Wilkie	12	26 June 1951	1100
Wilkie	11	27 June 1951	0900
Albatross	18	5 July 1951	1200
Albatross	18	6 July 1951	0600
Albatross	10	10 July 1951	0930
Albatross	10	11 July 1951	0600
Salinan	12	24 August 1951	
Robinson	10.4	9 October 1951	
Albatross	10.5	18 October 1951	1030
Salinan	15	22 October 1951	1508
Salinan	23	23 October 1951	1115
Salinan	20	23 October 1951	1345
Tuscarora	12	26 October 1951	1109

mmmm

TABLE 8
Echo-Ranging Detection Observations on
Surface Ship Targets of Opportunity

Target	Range	Date	Time
Unidentified Ship	18 kyd	13 February 1951	0945
Tanker	13	13 February 1951	1600
Tanker	16	15 February 1951	0815
Unidentified Ship	13	23 February 1951	0930
Merchant Ship	14	26 February 1951	1600
Merchant Ship	8	26 February 1951	1900
Merchant Ship	8	27 February 1951	0900
Merchant Ship	10	27 February 1951	0900
Tanker	15	1 March 1951	0930
Tanker	25	15 March 1951	0915
Merchant Ship	11	24 April 1951	0930
Merchant Ship	15	25 April 1951	1130
Merchant Ship	11	1 May 1951	0700
Merchant Ship	2	1 May 1951	1130
Unidentified Ship	4.5	1 May 1951	1130
DD and CL	18	5 July 1951	1300
Unidentified Ship	20	22 June 1951	1045
DD	12	6 July 1951	0600
PT	10	18 October 1951	1600
DD	18	18 October 1951	1600
Sarsfield	19	18 October 1951	1600
Tanker	7.5	18 October 1951	1300
Tanker	11	6 March 1952	1240
Freighter	13	7 March 1952	1048

Special receiving devices were used in the fifth and seventh operating periods; the Time Delay Receiver in the fifth and the Frequency Scanning Receiver in the seventh. The equipment operated at its best during the seventh operating period. Thirty detection observations made in these two periods were selected, as a group, for analysis. These observations were made when the equipment was operating according to design specifications and in good water conditions. Table 9 gives the pertinent information on the thirty detection observations made with special receivers.

From these tables histograms Fig. 27 were constructed of the number of times a target was observed in a given range interval, against that range. Curves were plotted (Fig. 28) of the frequency of occurrence of a target beyond a given range, against that range.

From Fig. 28, it is seen that the median range, the one at which an equal number of observations occurred at shorter and greater than this range, fell at

All targets	14.5 kyd
Submarine targets	16.5 kyd
"Special receivers"	18 kyd

For reasons described earlier in this chapter, the ranges listed above are probably less than the expected detection range for comparable targets in acoustic ducts.

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TABLE 9
Echo-Ranging Detection Observations on
Various Targets Using Special Receivers

Target	Range	Date	Time
Albatross	10.5 kyd	18 October 1951	1030
PT boat	10	18 October 1951	1600
Unidentified S/M	12	18 October 1951	1600
Unidentified DD	18	18 October 1951	1600
Cobbler	23	19 October 1951	1247
Sarsfield	19	18 October 1951	1600
Cobbler	20	19 October 1951	1510
Salinan	15	22 October 1951	1508
Salinan	23	23 October 1951	1115
Salinan	20	23 October 1951	1345
Cobbler	17.5	25 October 1951	1130
Chopper	18	25 October 1951	1458
Tuscarora	12	26 October 1951	1109
Sea Cat	20	30 October 1951	1416
Sea Cat	20	30 October 1951	1727
Sea Cat	20	31 October 1951	1014
Sea Cat	28	31 October 1951	1820
Sea Cat	24	1 November 1951	1624
Sea Cat	16	2 November 1951	0953
Tanker	11	6 March 1952	1240
Freighter	13	7 March 1952	1048
Chivo	13.3	10 March 1952	1558
Chivo	19	10 March 1952	1816
Chivo	20	11 March 1952	1401
Chivo	41	11 March 1952	1644
Chivo	11	12 March 1952	1115
Chivo	15.5	13 March 1952	1016
Chivo	13.8	13 March 1952	1128
Chivo	22.5	13 March 1952	1800
Chivo	34.6	14 March 1952	1014

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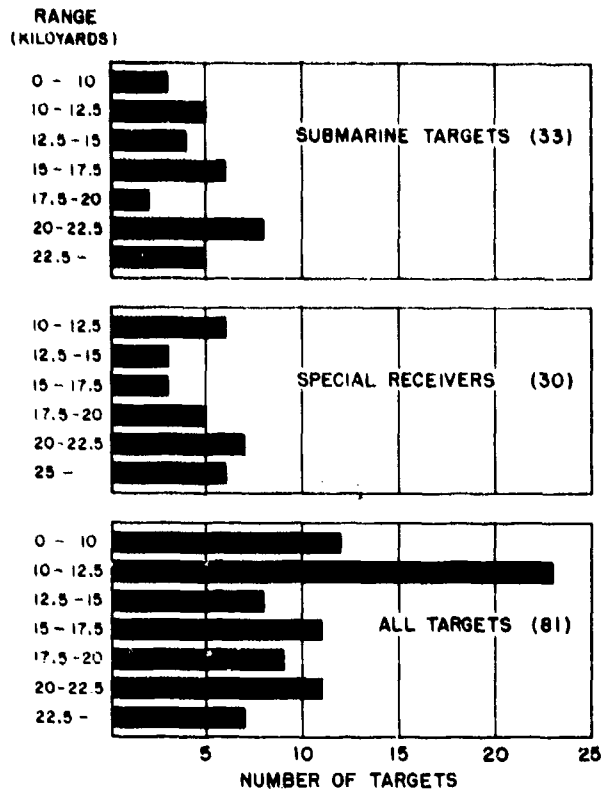


Figure 27 - Observed target detection ranges

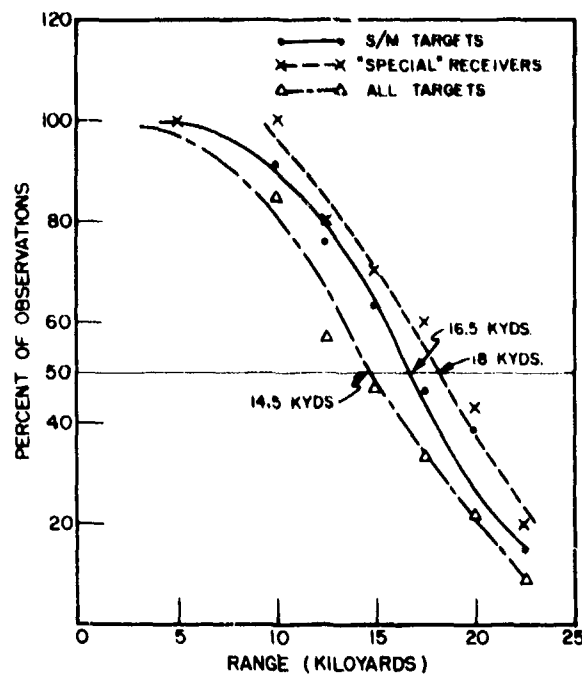


Figure 28 - Percent of contacts exceeding a given range

DETECTION OF ECHOES VIA BOTTOM REFLECTIONS

In the preceding section the capabilities of the LRS sonar in detecting targets in ducts were demonstrated. However, ducts do not always occur, as will be shown in the next section, and even when they do, an enemy submarine may avoid them by carefully choosing his depth. Hence, an alternative acoustic path is desirable, and reflections via the bottom provide that alternative path. The potential of this sonar in using the bottom-reflected path was studied.

It has been previously demonstrated that it is possible to transmit sound one way, by means of bottom reflections. In this program, the possibility of obtaining bottom-reflected echoes was established, but its feasibility as a method of search was not established. Table 10 lists ten situations where bottom-reflected echoes were obtained during the course of this program; six of the echoes were obtained from submarines. It also shows the calculated ranges at which reflections from the central ray would be obtained if there were no refractions, and if specular bottom reflection occurred. In addition it gives the interval of ranges covered by a beam 20 degrees wide.

The loss at reflection at the bottom was discussed in the section on propagation. Some measurements of this loss at reflection were made at zero angle of incidence and are listed in Table 11. These data reported in Ref. 20 were obtained at NRL in experiments not connected with the LRS program.

At 10 kc an average reflection loss of 11 db was found in deep water in the Caribbean south of Cuba, and in the Atlantic off the coast of Bermuda. In shallow water, off Key West, a reflection loss of 22 db was observed.

Several factors have been found to affect the magnitude of the reflection loss. These are the frequency, the angle of incidence of the sound beam, the type of bottom, and its contour. The dependence on frequency and bottom type are shown in Table 11.

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TABLE 10
Echoes Observed Via Bottom Reflection

Date	Time	Range of Observation	Tilt	Depth in fm	Target	Calculated Horizontal Ranges of Reflected Echoes	
						R ₁ kyd†	R ₂ kyd‡
1 May 1951	0700	11-13 kyds	30°	1800	Wilkie	14	11-21
1 May 1951	1845	9.5-10.6	25°	1500	Wilkie	14	10.5-23
30 Jun 51	1230	4-7.5	25°	1400	14 echoes Merchant Ship	14	9.5-22
16 July 51		8	0°	200	Sea Cat		
13, 14, 15 Aug 1951		1 kyd	30°	350	Chopper	2.8	2.2-4.1
31 Oct 51	1145	17.5	25°	2050	Sea Cat	19.3	14.5-31
1 Nov 51	1400	6	25°	800	Sea Cat	7.5	5.6-12
12 March 52	1417	12.5	30°	1800	Chivo	14	11-21
27 March 52	2000	7.4-8.2	30°	800	Sea Poacher	6.4	5-9.5
25 Oct 51*	0845	17.5-18	0°	110	Chopper		2.5-

*Multiple reflections obtained because of sharp negative gradients

†R₁ = range expected from central ray

(assuming specular reflection and no refraction)

‡R₂ = interval of ranges covered by a beam 20° wide

(assuming specular reflection and no refraction)

TABLE 11
Bottom Reflection Losses

Station	Loss in db at								Nature of Bottom
	3 kc	5 kc	7 kc	10 kc	15 kc	20 kc	25 kc	30 kc	
1	5	9.5	11	11	11	11.5	13	15	Clean, finely devoided sand
2	8	5	3.5	4	6	8	9.5	13	Black, gooey mud
3	13.5	17	20	22	22	21	21	23	Smooth, firm blue clay
4	10	15	18.5	18.5	19	19.5	21	22	10' soft mud over fine sand
5	3	2	1	1	2	4	6	8	Brown sticky mud

OCCURRENCE OF DUCTS*

One of the prime concepts of this report is that in order to gain long sonar ranges one must find suitable acoustic paths. This point of view was discussed at some length in Chapter I. The path which was studied most extensively was the surface-bounded duct, and in general the observations made in the course of the experiments and the conclusions drawn from the data relate to the situation where an acoustic duct exists.

During the course of the 10-kc program, bathythermograms were taken both regularly and frequently. An examination of the bathythermograms indicate that acoustic

*These ducts are all surface-bounded

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ducts occurred in a very high percentage of the cases. That is, acoustic ducts of 100 to 150-foot thickness were found or occurred at least 80% of the time in which sonar measurements were made. This observation indicates that the acoustic measurements here presented apply to acoustic ducts. They do not indicate, in themselves, how often such ranges may be expected to be obtained over all areas of the ocean. This point is emphasized because many measurements were made in deep water in the interval November to February in locations south of Cuba and in the Gulf of Yucatan. One would expect to find acoustic ducts a very high percentage of the time in those places and at those times of the year. This would not be at all indicative of the occurrence of acoustic ducts in general and therefore of sonar ranges.

The responsibility for obtaining data on the ocean-wide occurrence of ducts, is outside of the scope of this study. However, this section presents a summary and review of one analysis (Ref. 21) of the occurrence of acoustic ducts in one part of the North Atlantic ocean, extending from the North American coast eastward to the 65th meridian, and from 30°N to 40°N latitude.

The method of analysis in Ref. 21 involved first dividing the region into 2° squares - about 30 in all - and then combining the squares into four larger areas. For each 2° square, the report gave the number of BT's taken in it, the percentage in which ducts occurred and their mean depth. For the four larger areas, histograms were given of the duct depths occurring in each area. Each area was analyzed for the four seasons of the year.

Winter - January, February, March
 Spring - April, May, June
 Summer - July, August, September
 Autumn - October, November, December

The number of ducts observed, by areas and season, are listed in Table 12.

TABLE 12
 Number of Ducts Observed

Season	Area 1	Area 2	Area 3	Area 4
Winter	935	641	935	1137
Spring	1723	1342	1005	703
Summer	1531	1305	338	1148
Autumn	1040	1321	406	1108

The percent of time ducts were observed in this region, and the mean depth of the ducts are listed in Table 13.

From the histograms given for the four larger area (designated area 1, area 2, area 3, and area 4) the percentage of observation P in which ducts deeper than a depth D occurred, were obtained. P was plotted against D for each area and each season; the four curves pertaining to each season were plotted together in Fig. 29 to show spatial variations. Then for each area the autumn and winter curves were averaged to give a "cold weather" plot, and the spring and summer curves to give a "warm weather" plot. These are shown in Fig. 30.

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TABLE 13
Distribution of Ducts

Season	Percent of time Ducts Occurred	Mean Depth
Winter	94	290 ft
Spring	68	95
Summer	82	90
Autumn	93	195

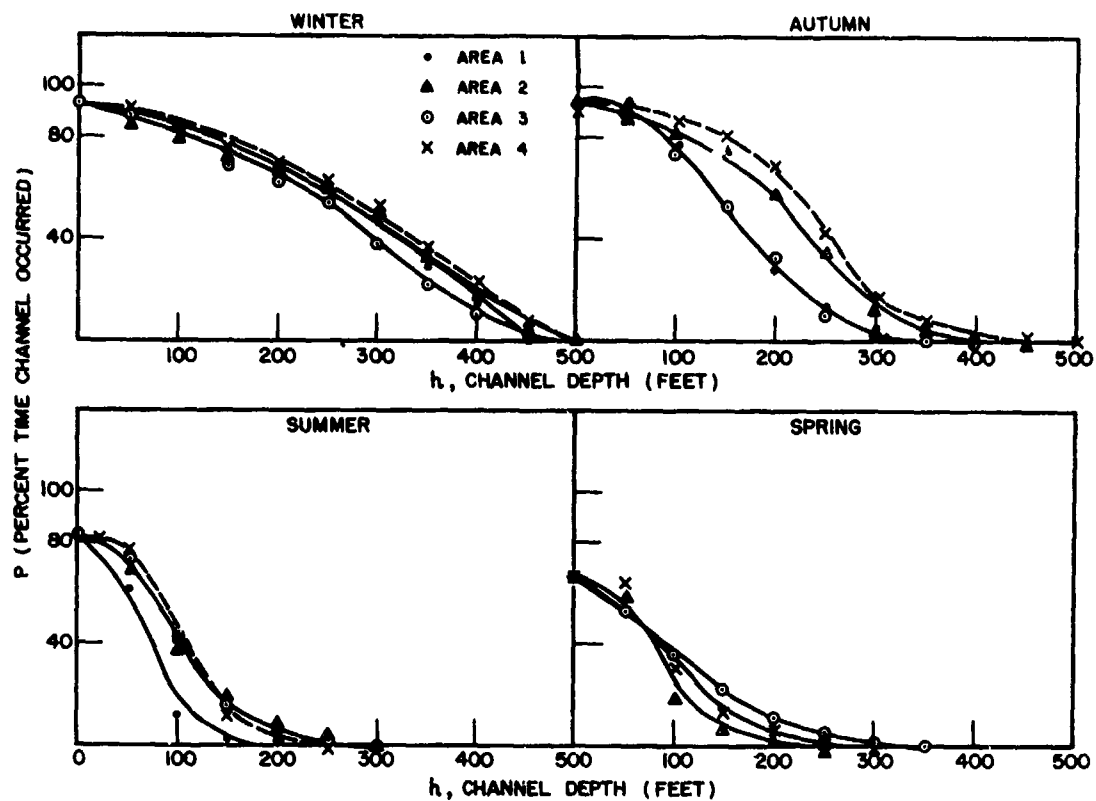


Figure 29 - Spatial variation of occurrence of ducts, by seasons

From the curves the frequency of occurrence of ducts at least 150 ft thick were noted. These are given in Table 14. The percentage of ducts of more than 150 ft thickness was selected for presentation because it was found observationally that good acoustic channelling occurs at 10 kc in ducts of thickness of 150 ft, or more. (Ducts of less thickness may on occasion be good. See Chap. IV for a full discussion).

From Table 14 it may be seen that, for the "cold weather" period of six months, ducts 150 feet or more thick may be expected more than 50 percent of the time. In the "warm weather" period of six months they may not be expected as much as 1/4 of the time.

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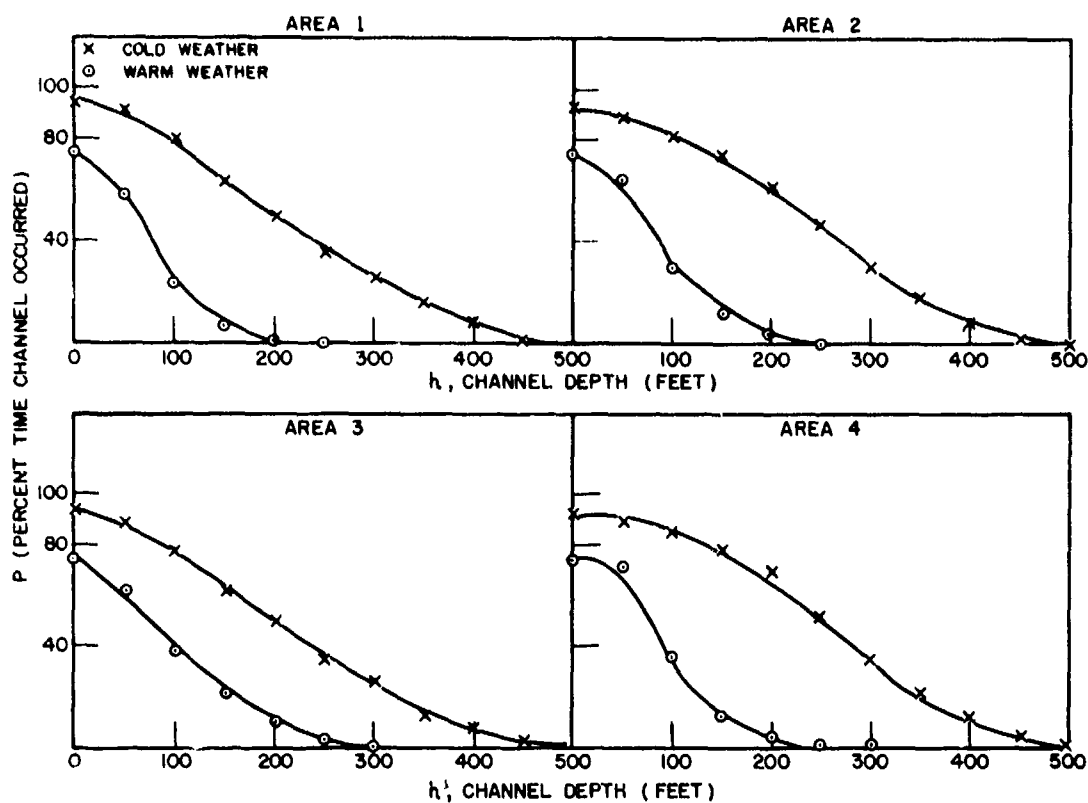


Figure 30 - Seasonal variation of occurrence of ducts, by areas

TABLE 14
Occurrence of Ducts
150 Ft Thick or More in Percentages

Season	Area 1	Area 2	Area 3	Area 4
Winter	77%	74%	72%	77%
Spring	12	22	7	14
Summer	2.5	18	18	12
Autumn	52	76	53	81

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IV - DISCUSSION

In this part of the report, the implications of the experimental results are examined. It is shown that the results actually obtained are consistent with the theory presented.

A new empirical formula for the transmission loss in surface-bounded ducts is obtained and explained, and, from it, a method of range prediction is formulated and applied to the experimental gear for the noise-limited case. Extension to reverberation limitation is also carried out. Finally, the potentiality of an improved feasible sonar equipment is explored, using range predictions. Topics discussed include optimum processing of a single echo and optimum utilization of multiple echoes leading to a comparison of searchlight and scanning sonars. The advantages of variable-depth sonar are also discussed.

PROPAGATION THEORY AND RANGE PREDICTION

Echo-Ranging Equation for Noise Limitation

The echo-ranging equation for the noise-limited case is given in Chapter I as

$$E = E_1 - \text{Losses} \quad (1)$$

E_1 was delineated by the equation

$$E_1 = (I_1 + T) - (N - \Delta + \delta) \quad (2)$$

in which the parentheses set off echo level at 1 yard range and echo level required for detection. All terms were defined in Chapter I. For ready reference of definitions and units see Appendix B.

Observations Obtained with the Experimental 10-kc System

For the experimental 10 kc system, the following values as given in Chapter II may be substituted in Eq. (2)

$$\begin{array}{rcl} I_1 & = & 131 \text{ db} \\ T & = & 20 \text{ db} \\ -N & = & 51 \text{ db} \\ \Delta & = & 25 \text{ db} \\ -\delta & = & -13 \text{ db} \\ \hline E_1 & = & 214 \text{ db} \end{array}$$

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Reference to Eq. (1) shows that losses of this same amount, 214 db, would result in zero echo excess (i.e., 50% probability of detection).

With gear of the above proficiency, detection ranges in ducts varied from 10 kiloyards to 40 kiloyards. In all cases in ducts, divergence loss was approximately spherical to 1000 yards (120 db loss) and cylindrical thereafter ($20 \log R$, R in kiloyards). The total divergence loss amounts to 144 db at 15 kyds range leaving an attenuation of $214 - 144 = 70$ db for the round trip, or 2.3 db/kyd. At 40 kyd, it amounts to 152 db leaving an attenuation of $214 - 152 = 62$ db for the round trip, or 0.8 db/kyd. Values of attenuation coefficient, α , encompassing these limits have been observed in one-way measurements at 10 kc.

Via the bottom, only some thirty-odd echoes were obtained. Here the losses would be expected to be spherical divergence loss all the way, bottom-reflection loss and absorption. On the occasion when a bottom-reflected echo was obtained from 17 kiloyards slant range, the divergence loss was $40 \log 17000 = 169$ db. Absorption is estimated at 0.5 db/kyd on the assumption that average temperature over the path is 60°F (Eq. (7) in Chapter III), giving 17 db for the round trip. This leaves a reflection loss of 14 db going out and 14 db returning.

At the time that target strength was measured via the bottom, a reflection loss of 21 db at each reflection was observed. In deep water in the Caribbean Sea, bottom reflection loss was determined in one-way measurements to be 11 db. In shallow water off Key West a range of about 8000 yards was commonly observed with no transducer tilt when there was a negative temperature gradient. Echo excess of 20 db is estimated under these circumstances. This can be accounted for if

$$\text{Divergence} = 156 \text{ db}$$

$$\text{Attenuation} = 7 \text{ db}$$

$$\text{Reflection Loss} = 2 \times (15.5 \text{ db})$$

The total loss will be 194 db. On the whole there appears to be some degree of consistency in all these indications of reflection loss.

A loss of 15 db per reflection is costly, and rules out echoes via the bottom with this equipment in very deep water even at a range of 10 kyd. Methods for obtaining improvements are discussed later.

Mathematical Formulation of Losses in Ducts

Propagation losses in ducts are of three types:

1. Divergence or spreading loss
2. Leakage
3. Absorption

The divergence and absorption losses can be calculated. The sum of these two, when subtracted from the observed loss, yields a remainder which is ascribed to leakage.

Divergence Loss - When there exists at the surface a layer in which there is a positive velocity gradient (velocity increasing with depth, a condition which holds for

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example in isothermal water), there is upward refraction. The sound rays are arcs of circles between successive incidences on the surface. (See Fig. 31a.)

It is shown in Appendix A that the limit ray in extending from the surface to the bottom of the layer and becoming tangent to the lower boundary travels an approximately horizontal distance*

$$X_1 = \rho \theta_1 = \sqrt{2 \rho h} \quad (8)$$

in which ρ is radius of curvature of the ray

θ_1 is angle with the horizontal at the surface

h is duct thickness.

This distance is labelled X_1 in Fig. 31a. The formula proves generally useful. In travelling to a range X_1 given in Eq. (8), sound experiences a transition from spherical to cylindrical divergence. Beyond X_1 there is no further average spreading vertically and therefore cylindrical divergence holds. The actual one-way spreading loss is shown to be equivalent to spherical to a range $X_1/2$ and cylindrical thereafter minus 3 db (Appendix A). Divergence loss in a duct for the round trip out and return is then

$$40 \log \frac{X_1}{2} + 20 \log r / \frac{X_1}{2} - 6 \quad (9)$$

or

$$\text{Divergence loss} = 20 \log \frac{X_1}{2} + 20 \log r - 6$$

in which r is range in yards and X_1 is also in yards.

This spreading loss is particularly important in the first 1000 yards amounting in most cases to 120 db, a large portion of the total loss E_1 which can be taken.

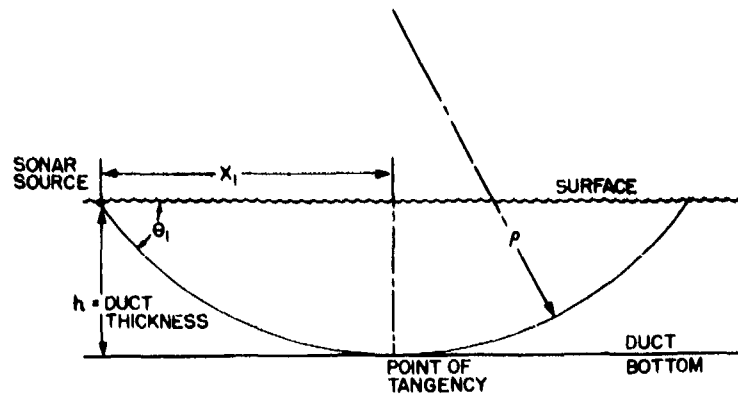
Leakage Coefficient - The leakage out of a duct by reflection from a rough surface is expressible in terms of a leakage coefficient, α_L , in decibels per kiloyard. In addition to being usually the greatest contributor to loss at long range at 10 kc, leakage is also the most highly variable of the losses.

This leakage coefficient is dependent upon duct thickness and temperature gradient in the duct. It is considered self evident that leakage by reflection from the surface is proportional to the percentage of trapped power incident on the surface per kiloyard of transit. It follows, taking Eq. (A-10) into account that

$$\alpha_L \propto \frac{1}{\sqrt{\rho h}} \quad (10)$$

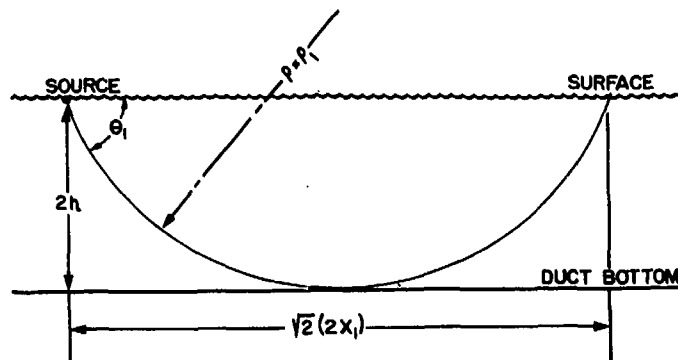
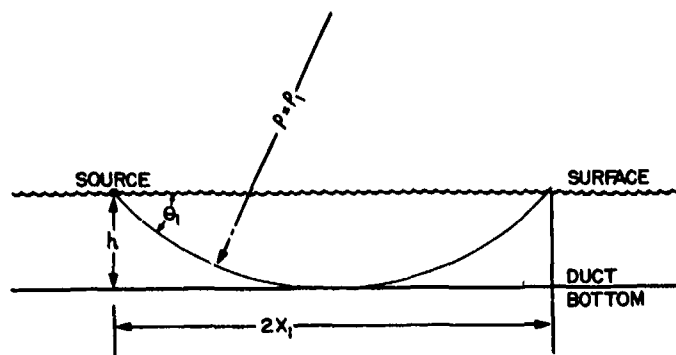
Whenever h is doubled, α_L is decreased by the factor 0.7. Likewise, and this is a point largely ignored in the past, if the radius of curvature is doubled, the leakage is decreased

*Strictly speaking $\rho \theta_1$ is the length of the arc. With $\rho = 90,000$ yds and $h = 100$ yds, the difference between X_1 and the arc is negligible. In Fig. 31, h is greatly distorted.



NOTE: θ_1 IS MAGNIFIED ABOUT 10 FOLD BY CHOICE OF SCALE. ACTUALLY θ_1 IS USUALLY LESS THAN 3 DEG.

(a)



(b)

Figure 31 - Schematic diagram of ray paths in ducts showing
(a) Geometry of limit ray in ducts
(b) Doubling of duct thickness

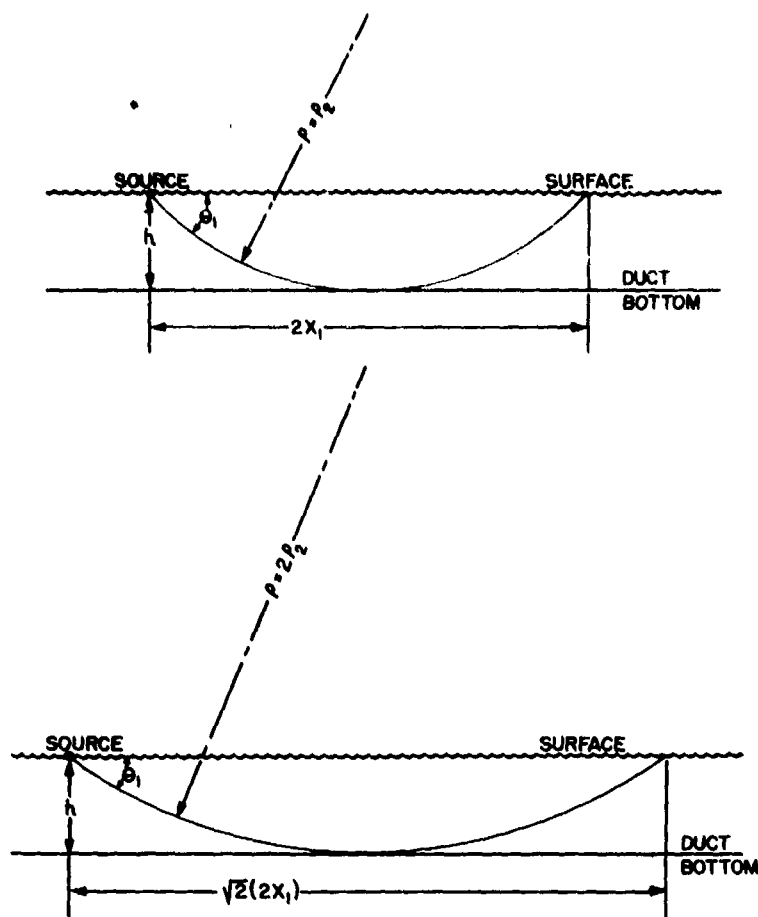
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Figure 31 - Schematic diagram of ray paths in ducts showing
(c) Doubling radius of curvature

by a factor of 0.7. Since ρ is increased by slight negative temperature gradients in the duct, α may vary several-fold depending upon temperature gradient in the duct. Figure 31 b shows the effects of doubling duct thickness, h ; while the effect of doubling radius of curvature is depicted in Fig. 31 c.

The dependence of α_L on sea state has been determined empirically to be, at 10 kc,

$$\alpha_L \propto 1.4^S \quad (11)$$

where S is sea state.

Combining all the contributors to α_L , we find that the formula for α_L at long range is

$$\alpha_L = \frac{1200}{\sqrt{\rho h}} (1.4)^S \quad (12)$$

In (12) the proportionality constant is chosen empirically to fit the data, with ρ and h both in yards.

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Absorption Coefficient - The last contributor to propagation loss to be considered is absorption. The value of absorption coefficient α_0 is known from laboratory measurements at 10 kc; it is approximately

$$\alpha_0 = \frac{28}{t} \text{ db per kiloyard} \quad (7)*$$

t being temperature in degrees Fahrenheit.

Discussion of Propagation Loss

The whole loss for the round trip in echo-ranging may now be written.

$$\text{Loss} = 20 \log \frac{X_1}{2} + 20 \log r - 6 + 2 (\alpha_0 + \alpha_L) R \quad (13)$$

in which x_1 , α_L and α_0 are given respectively by Eqs. (8), (12) and (7), X_1 and r are in yards and R is range in kiloyards.

Suppose $h = 50$ yds, $\rho = 90000$ yds (isothermal water) $t = 80^\circ \text{F}$, and sea state is 2.

For this case

$$\frac{X_1}{2} = 1350 \text{ yd from (8)}$$

$$\alpha_0 = 0.35 \text{ db/kyd from (7)}$$

$$\alpha_L = 1.04 \text{ db/kyd from (12)}$$

$$\begin{aligned} \text{Loss} &= 63 + (60 + 20 \log R) + 2.78R - 6 \\ &= 117 + 20 \log R + 2.78R \end{aligned}$$

(Note that $20 \log r = 60 + 20 \log R$). We may now tabulate loss versus range, R, as follows

<u>R(kyd)</u>	<u>Loss</u>
5	145 db
10	165 db
20	199 db
25	215 db

Under these conditions, 10-kc equipment should give about 25 kyd range (Echo excess at 1 yard has been given as 214 db).

A set of loss curves including everything except absorption loss can now be made up. $2 \alpha_0 R$ is more conveniently separated as will be shortly explained so that the loss curves include divergence and leakage loss. Assume, as a standard condition, $\rho = 90000$ yd, $h = 50$ yd, transducer depth = 0, sea state = 2 and $t = 60^\circ \text{F}$. The loss is computed for the

*Repeated from Chapter III.

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standard case in the above example. Thereafter, each doubling of h or ρ decreases α_L by a factor of 0.7. Likewise, approximately, each decrease of 1 in sea state decreases α_L by a factor of 0.7. So, by plotting a family of curves in which α_L is changed by successive use of the factor 0.7 for better conditions and 1.4 for worse conditions, we may start at the standard curve and step along one curve in the right direction for each doubling or halving of h or ρ and for each step change in sea state, thereby selecting the right curve. This family of curves is plotted in Fig. 32. The standard condition yields curve 0; positively numbered curves are improved and negatively numbered worsened by the number of steps indicated by the curve number.

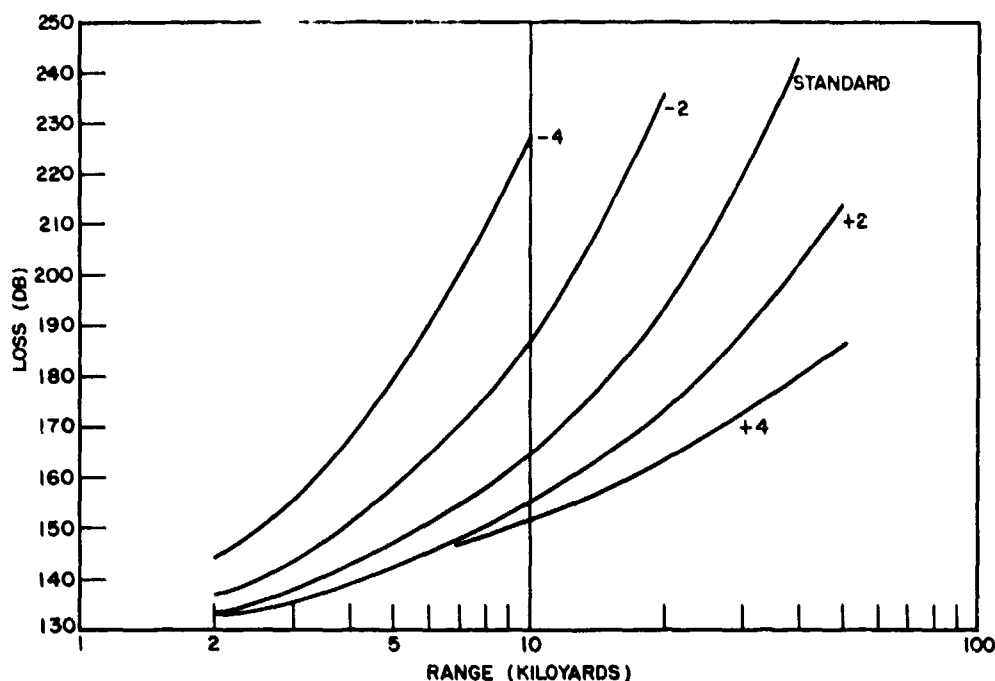


Figure 32 - Round trip propagation losses (exclusive of absorption)

In computing the above set of curves, allowance has been made for the expectation that worse conditions on the average include an effect on the divergence loss, arising from a change in X_1 .

To alleviate a difficulty in determining the value of ρ , Table 15 appended to the curves in Fig. 32 indicates the number of curves improvement from -2 to +2 (for different values of ρ) as a function of temperature and temperature gradient, which can be determined from the bathythermogram.

Let us follow an example: Duct depth 60 ft, (about one curve poorer than standard), temperature gradient -0.3° F per 100 feet at a surface temperature at 80° F (from Table 15, two curves better than standard), and sea state 4 (two curves worse than standard). This all adds up to 1 curve worse than standard. This curve would fall about midway between curves 0 and -2.

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TABLE 15
Steps Improvement as a Function of
Temperature and Temperature Gradient
(Fig. 32)

Steps Improvement	$\frac{\partial t}{\partial y}$ (°F per 100 Ft)		
	40° F	60° F	80° F
2	-0.15	-0.22	-0.3
1	-0.10	-0.15	-0.2
0	0	0	0
-1	0.2	0.3	0.4
-2	0.6	0.9	1.2

Range-Prediction Chart for Ducts

The echo-ranging equation (1) may be rewritten in the form

$$E = (E_1 - 2 \alpha_0 R) - (\text{Divergence Loss} + 2 \alpha_L R) \quad (14)$$

The terms in the last parentheses are already plotted in Fig. 32. If the terms in the first parentheses are independently plotted on the same graph, the echo excess is the difference between the two curves which difference falls to zero where the curves intersect. The curves for the terms in the last parentheses constitute a family as already shown. The curves for the terms in the first parenthesis constitute a second family comprised of curves for different temperatures, α_0 being a function of temperature. In Fig. 33, both families are plotted using $E_1 = 214$, as computed, for the experimental gear.

The better curve of the $E_1 - 2 \alpha_0 R$ family generally applied in the Key West area because water temperature was high. Ranges of approximately 15 to 40 kyds are predicted and were obtained. Correlation between maximum ranges for the day and predictions is good. However, it is now realized that even greater precision in range predictions can probably be obtained by having prediction curves prepared in advance and by observing deviations from these curves on a day-to-day basis, leading eventually to corrected curves of known reliability limits.

Reverberation Masking in Ducts

In view of the fact that there has been no standardization of terminology concerning reverberation masking and limitation, it is deemed advisable to define the terminology used in this report. It is desired to clarify by definition a set of changing conditions after a ping in which the predominant interference is first reverberation. A little later reverberation has died down to a point where it is not discernible and noise is the predominant interference. In the first region we have reverberation masking; we do not have reverberation limitation unless maximum detection range falls in this region. In the second region, there is noise masking, and, when echo excess dies to zero in this region, noise limitation exists.

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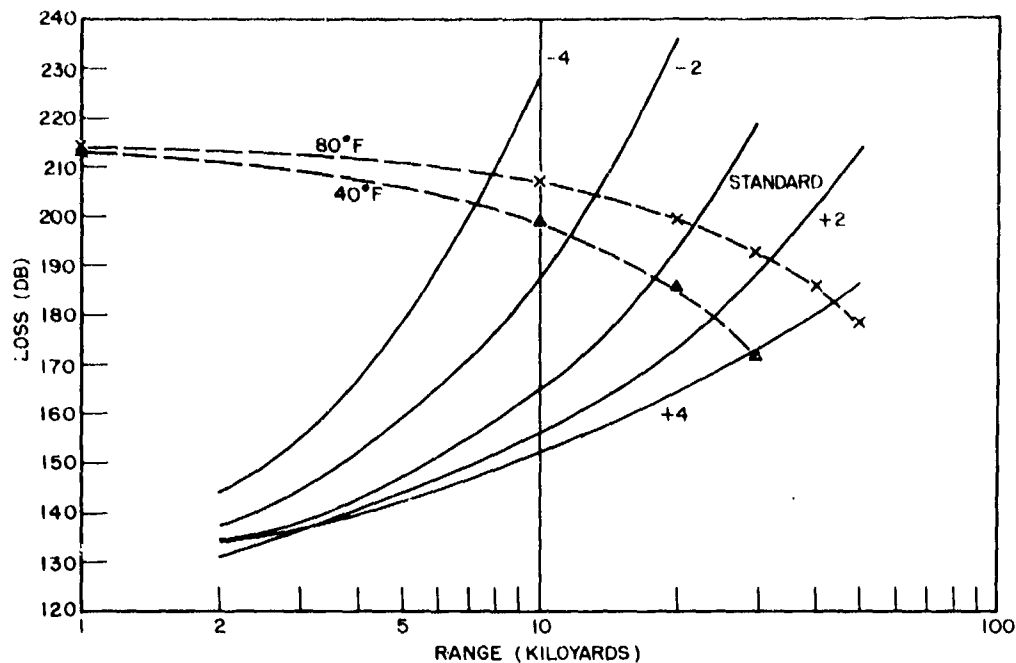
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Figure 33 - Range prediction chart (noise limiting case)

Echo excess (as defined in Chapter I) is the excess in decibels of the echo level over the level required for a 50% probability of detection. There is an echo excess relative to noise and also an echo excess relative to reverberation.

Figure 34 is a typical graph of echo excess relative to noise and echo excess relative to reverberation, both plotted against range. Various regions of this graph will be referred to as illustrative of the following definitions.

Reverberation masking is a condition which exists when the echo excess relative to reverberation is less than that relative to noise. In Fig. 34 this condition exists out to range R_1 .

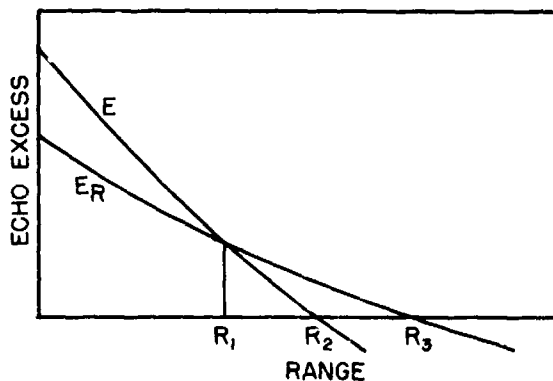


Figure 34 - Echo excess relative to reverberation and noise

Noise making is a condition which exists when the echo excess relative to noise is less than that relative to reverberation. In Fig. 34, this condition exists beyond range R_1 .

Noise-limited range is the range at which echo excess relative to noise becomes zero. This range is R_2 in Fig. 34.

Reverberation-limited range is the range which echo excess relative to reverberation becomes zero. This range is R_3 in Fig. 34.

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If R_2 is less than R_3 , as in the figure, a condition of noise limitation exists. If R_3 is less than R_2 a condition of reverberation limitation exists.

In this section, attention will be directed to echo excess relative to reverberation. An attempt is made here to present for the first time an expression for echo excess relative to reverberation which involves sea state and duct characteristics. The assumption is made that the back scattering is proportional to leakage out of the duct. This would be true if the scattering pattern were always the same. Departures from this assumption will be determined in future work.

The derived equation is

$$E_R = 6 + 5 \log \rho h - 1.5S - 10 \log \tau - 10 \log BW - \delta_R - 10 \log R \quad (15)$$

in which

E_R is echo excess relative to reverberation,

ρ is radius of curvature of rays in the duct,

h is duct thickness,

S is sea state,

τ is pulse length in seconds,

BW is beamwidth between the 10-db points,

δ_R is recognition differential relative to reverberation and

R is range in kiloyards.

The constant is chosen to make $E_R = 11$ db at 10 kyd under standard conditions with no doppler shift in accord with observation. Since $\delta_R = 6$ db with no doppler shift, the signal level must be 17 db above the reverberation level for $E_R = 11$ db, as discussed in the previous chapter. Since δ is less with larger and larger doppler shifts down to -9 db, E_R may be as large as 26 db at 10 kyd.

Note that ρ , h , and S are introduced for the first time to our knowledge; an extension of the reasoning by which α_L was derived introduces these terms. Interpreting the effect of these quantities, (a) under standard conditions, the reverberation-limited range is 100 kiloyards, and (b) when ρ and h are small and S large (4 to 6), the reverberation-limited range is much shorter. Noise limitation still exists, however, as shown in Fig. 35. Design parameters may be imagined where reverberation limitation would occur. These would involve much higher power or much lower directivity or much longer pulses, much higher noise levels or combinations of these changes.

Range Prediction Against Targets Below Ducts

Against targets below the duct, the range is to a great extent regulated by the ray pattern. Figure 36 depicts such limitation for an arbitrary ray pattern with the transducer at zero depth and at target depth. Referring to the figure, it is obvious that the range is doubled in going from substantially zero depth to a transducer depth equal to that of the submarine below the duct.

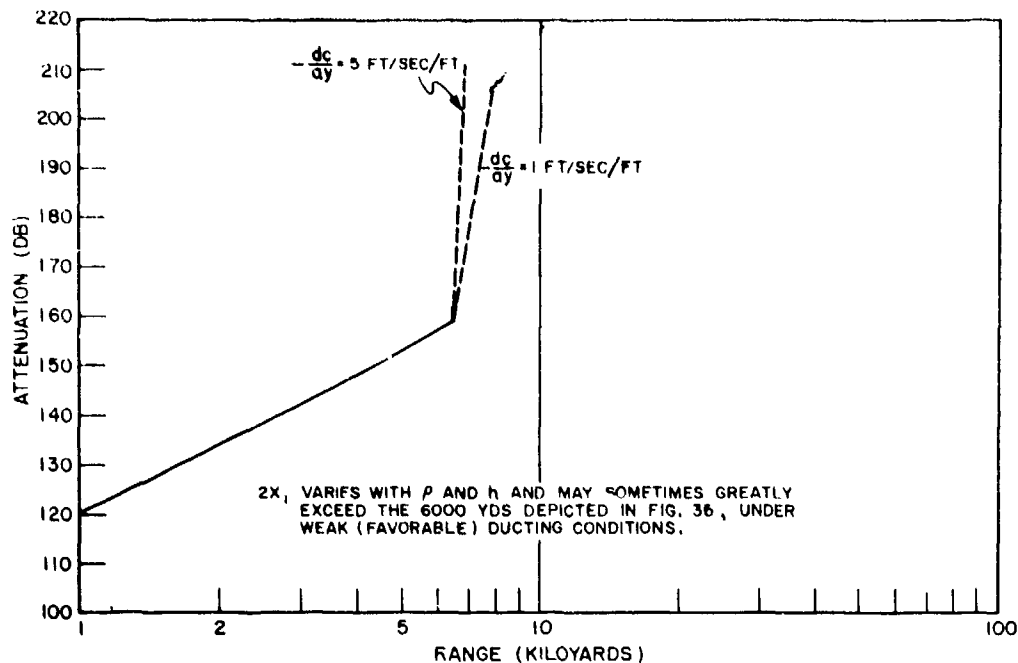


Figure 37 - Detection range, target below duct

For most cases, then, the range is limited to about that predicted by ray theory. For a deep transducer this is $2X_1 + 500$ yd., approximately, X_1 having been defined in Eq. (2). X_1 varies with ρ and h . Under standard conditions $2X_1 + 500 = 6500$ yards.

Predictions of Range via the Bottom

While range via the bottom is much more difficult to pin down because of paucity of data and high variability of apparent reflection loss, it appears that some progress has been made. In discussions on this subject, it must be taken into account that reflection loss is dependent upon the composition of the bottom, the grazing angle, and the frequency. It must also be recognized that observed reflection loss at the bottom over any path was not minimized by varying the train and tilt of the transducer, so that the slope of the bottom could have affected the results adversely. However, it has rather definitely established that loss is spherical divergence loss, plus absorption, plus reflection loss. Thus $E = (E_1 - 2\alpha_0 R) - (40 \log r + 2nK)$ in which K is average reflection loss per reflection, n is number of reflections from the bottom one way, and r and R are range in yards and kiloyards respectively.

A double family of curves may be made up in which $E_1 - 2\alpha_0 R$ is reproduced as a family exactly as in Fig. 34, and in which the second family in Fig. 35 is replaced by $40 \log r + 2nK$ for different values of nK . If nK is permitted to vary from zero to 50 db in 10 db steps, we obtain the family of Fig. 38, which is a prediction chart.

In using this chart at 10 kc, n will be unity except in very shallow water. Also, very low values of K will not be expected in deep water because of the unfavorable grazing angle required for the ranges of which this equipment is capable. The most probable value of K would seem to be about 15 db. For this value, the chart predicts a range of 13 kyd for the experimental gear.

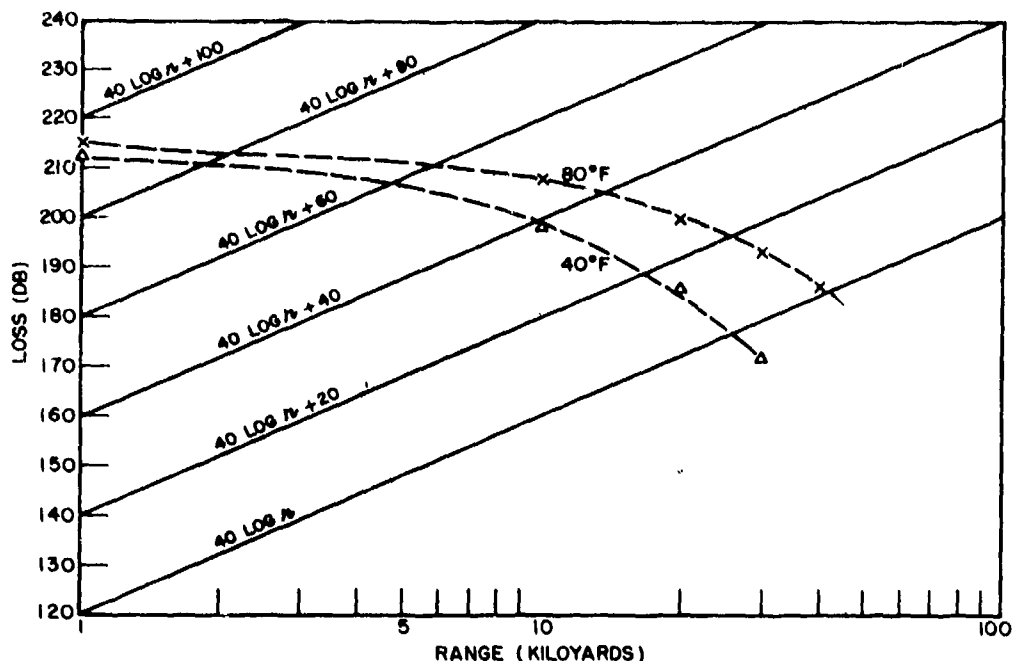


Figure 38 - Range chart for bottom reflected path

OPTIMIZING SIGNAL PROCESSING

Discussion thus far has compared ranges with a single E_1 under a great variety of water conditions. It appears to be in order to assess the feasibility of improving E_1 . Signal processing contributes to E_1 through the recognition differential, δ .

This Laboratory has fully developed and proved a device which substantially improves signal processing of a single ping, namely the Frequency-Scanning Receiver. The principle on which this device works is that signal-to-noise ratio may be improved for weak signals by filtering out all noise except that in the neighborhood of signal frequency. Reference 23 indicates that for weak signals the optimum bandwidth is $2/\tau$, where τ is pulse length.

A further consideration in determining the optimum bandwidth of the filter is the frequency spectrum of the echo. If this spectrum is very narrow, then the above bandwidth may indeed prove optimum, but if distortion has broadened the spectrum of the echo, the optimum bandwidth will be greater. The extent to which the echo is distorted by frequency modulation can be studied with the aid of the graphic indicator. With echoes of one-half second duration from short ranges to insure good signal-to-noise ratio, indications are that a nearly constant frequency actually exists in the echo, as evidenced by the ability of the operator to obtain a presentation of the echo which is substantially a straight line. Also, one-way transmission in ducts at 1 kc to a range of 73 miles indicates, on the graphic indicator, no more frequency modulation than can be accounted for by the imperfections of the recorder used. While the evidence is not conclusive, such as there is tends to support the contention that the optimum bandwidth is $2/\tau$ for echoes of at most one second duration. Beyond this pulse length, evidence is not at hand.

The Frequency-Scanning Receiver used in the 10-kc experimental work had 29 channels, each 7 cps wide to cover doppler shifts. This fell short of optimum for the pulse

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lengths of 0.5 and 1 second customarily used. Yet this signal processor gained about 7 db over the ear. Reference to Fig. 33 will disclose that a loss of 7 db would reduce a 40-kyd maximum range to 34 kiloyards with approximately equal percentage reduction at shorter ranges. The cost of this 7 db in complexity and weight, is deemed not too high a price for this sort of improvement. The cost becomes less at still lower frequencies because of the lower doppler shift encountered. Long pulses are essential if high gains are to be realized by this approach.

The Laboratory also has developed means of processing a succession of echoes in order to capitalize on echo fluctuation. This means is the Time-Delay Receiver described under "Equipment" in Chapter II. This also gained about 7 db relative to the ear. It seems logical to suppose that this device might gain another 5 db when used in combination with sharp filters. The Laboratory is pursuing the development of a combination device of this kind.

Another approach looks about equally promising. Basic research in signal and noise analysis has made excellent progress and new conditional-response computers are in the offing. At present, however, it can at least be said that techniques for obtaining recognition differentials on a multiplicity of pulses as favorable as 8 db are certainly available.

OPTIMIZING OTHER EQUIPMENT PARAMETERS

Equation (2) shows that additional improvement in E_1 may be achieved by increasing I_1 and Δ . In the SQS-14, which has been built by a manufacturer since the completion of the experimental work at 10 kc, the active diameter of the transducer was increased from 3 ft. to 3.5 ft. This resulted in improving both I_1 and Δ for a total gain of 3 db. In addition, the power has been increased fourfold for a gain of 6 db more. Shorter pulse length, 0.25 second, loses nearly 3 db, but this loss does not have to be accepted in an optimum equipment; so that a net gain of 9 db is feasible without excessive increase in dimensions. If an improved δ (down to 8 db as compared to 13 db for the NRL equipment) were included, there would be obtained a sufficient increment in E_1 (viz. 14 db) to overcompensate for the higher noise level on a 15-knot destroyer. In fact under this condition, $E_1 = 217$ db.

There is no need to stop here. With the same transducer dimensions, a decrease in frequency to 5 kc would give considerable improvement in ducts and via the bottom, even though E_1 would drop from 217 to 200 db. Under standard conditions and with surface temperature of 80°, a range of 40 kyd should be obtainable in the duct at this lowered frequency. It perhaps should be reiterated that this performance is at the self-noise level of a 15-knot destroyer. Conditions two steps better should increase this range to about 65,000 yd, while conditions two steps worse should decrease the range to 20,000 yd.

Via the bottom, a loss of 10 db per reflection would permit a slant range of about 20,000 yd with such a 5-kc equipment at this range, the grazing angle would be decreased so that some such improvement in reflection coefficient relative to 15 db at 10 kc appears reasonable.

EMPLOYMENT OF SONAR EQUIPMENT

Scanning versus Searchlight Sonar

The observed successes of SQS-4 at 14 kc and SQS-5 at 10 kc have placed scanning sonar in a preferred category. Certainly, the utilization of some 20 times as many pings

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in any given direction offers an improved chance of recognition of some echoes among the highly fluctuating succession of echo levels. The increased number, with a presentation as in the Time-Delay Receiver should gain 9 db, but, since the scanning sonar presentation does not lend itself so well to a comparison of many successive pings, the gain from repeated coverages in scanning sonar is estimated at 5 db. Furthermore, the psychological effect resulting from the knowledge of all-around coverage on every ping is important. All-around listening can provide torpedo detection not available with searchlight equipment in normal search procedure.

On the other side of the ledger, searchlight equipment concentrates all of its energy in a beam resulting in about 10 db gain in intensity for the same power when cavitation level is not reached. Searchlight gear also spends the full time of a ping cycle looking in one direction. This mode of operation gains about 10 decibels relative to the time-sharing of scanning sonar. Signal-processing devices have been developed for searchlight gear that gain 10 or 12 db more, but they are not available for present scanning sonars.

The net gain of some 25 decibels with searchlight gear approximately doubles the range in ducts and can be turned into a 60% to 80% increase in swath width.

Much stress is placed today on utilization of the same equipment for both search and attack. It is generally conceded that SQG-1, a searchlight gear, is better than any scanning sonar can be expected to be for attack. Advantages are the tilting beam which enables maintenance of contact at all depths, improved bearing information resulting from the use of SSI, and improved range information resulting from a more definite determination of hull position when the echo is not obscured by wake echo resulting from unbeamed insonification. In trials of the Mark 102 Fire-Control Equipment, the equipment failed with QHB but worked well with SQG-1.

The position is taken that most of the advantages of searchlight gear, except tilt (and here MCC may be an acceptable substitute), can be incorporated in scanning sonar. Some of these advantages are available in SQS-5 which has searchlight and tribeam modes of operation. Add to these features a longer pulse and improved signal processing and the searchlight mode of operation with this scanning sonar seems likely to emerge as the preferred search procedure. (This does not apply to dipped sonar treated later.) All-around listening for torpedoes can be carried out simultaneously.

For improved PPI presentation of echoes, when desired, the use of preformed beams would enhance results (tests of the QHD are regarded as nonconclusive). Another approach to scanning sonar with the elimination of time-sharing before filtering is being developed by this Laboratory, with resulting lighter-weight transducers as an added dividend.

For attack, the modified SQS-4 - Mark 5 combination has appeared promising in trials in the USS SARSFIELD. Utilization of the Sonar Graphic Indicator and the Sector Scan Indicator should be considered as possible further improvements.

Variable-Depth Sonar

As a rule, acoustic paths to the target in ducts are best with a shallow transducer. Furthermore, hull-mounted transducers pick up less self-noise than transducers towed at shallow depth. The only gain in towing, insofar as detection of targets in ducts is concerned, is in the relative freedom from quenching which towing provides in a heavy sea.

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If the transducer is towed near the bottom of the duct, the energy trapped falls off so drastically that range in the duct may be cut 50% or more. However, the gain in range against targets below the duct cannot be disputed (see Fig. 36). If it is considered highly important to detect targets at as long ranges as possible below the duct while retaining very long ranges in ducts, two transducers, one towed below the duct, appear essential. Normal power output of the towed transducer could be low. (Note in Fig. 37 that the range would not be greatly decreased by lowering the $E_1 - 2 \alpha_0 R$ curve by several db).

Sometimes the near-surface duct is submerged, because of "afternoon effect," below the depth of the hull-mounted transducer. Here towed sonar would definitely gain. Also, in some areas, submerged ducts occur below surface-bounded ducts. If a towed transducer were available, it could be used in submerged ducts at increased power when such ducts exist.

Dipped Sonar

Dipped sonar is a reality in helicopters and blimps. A long-range dipped sonar at 2 kc for blimps is planned by the Naval Research Laboratory and may be applicable also to new helicopters of greater carrying capacity. The extension of this kind of operation to ships can hardly be dismissed without at least considering its advantages. The concept of dipped sonar presupposes a mode of operation involving alternating dipping and transiting periods. The advantages are increased range resulting from lower noise level, and increased average forward speed achieved by removing the restriction on speed imposed by operation of the sonar under way. Another advantage, less obvious, is that the enemy has no way of predicting where the search ship may leap and may either be forced to stay deep, or risk detection by pings from an unanticipated nearby search ship which has withheld pinging while closing.

This mode of operation is certainly not attractive when ranges are short since the slowing and speeding up of the ship would have to be repeated at short intervals. However, when ranges of the day are 25 miles or greater, a search ship slowed to 7 knots could cover a circle of 25 miles radius in a few minutes (here scanning sonar is much better than searchlight) then steam at 30 knots to its next position 15 to 20 miles away, averaging possibly 25 knots forward speed for the whole operation with double the swath width obtainable while pinging underway at 25 knots. This possibility deserves serious consideration.

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V - CONCLUSIONS

Since the objectives of the problem were to establish feasibility and to make use of the equipment as a tool for research, the conclusions fall naturally into categories of feasibility and research results.

FEASIBILITY

In the "feasibility" category, the key conclusion is that long average ranges are obtainable in ducts with the experimental equipment mounted in a submarine. Other conclusions in this category which are less direct or more specific in nature, follow.

Reduction in frequency from that of the conventional 20-kc equipment to 10 kc, together with improved equipment parameters, has proved an effective approach toward increasing range materially. Ranges now obtainable are several times those of World War II equipment.

Either hull-mounted or towed 10-kc sonar for surface ships can be built to give ranges comparable to those in the GUAVINA, with the higher noise level compensated by higher power and slightly larger transducer size.

A moderate extrapolation of data to still lower frequency indicates the probability of substantially greater ranges than at 10 kc even with the same transducer diameter, the same power, and the same recognition differential.

It is feasible to obtain an efficient, economical transducer at 10 kc to handle output powers up to 2.5 kilowatts in an 18° beam, and to train this transducer accurately in a submarine installation.

The feasibility of mechanical storage of energy instead of electrical storage has been established by the employment of a rotating-machinery, a-c supply with three-phase, full-wave rectification.

Special receivers have been successful in significantly improving recognition differential. An advantage of a display in the form of a long-persistence or permanent record has been found to exist.

Fleet equipment should be substantially simpler than the experimental equipment because the choice among optional components will already have been made and because fleet equipment is not intended for research. A simple monitor for checking performance would, however, be useful in fleet equipment.

RESEARCH RESULTS

In the category of research results, a large body of data has been obtained, selected samples have been reported in Chapter III, and an analysis has been given in Chapter IV. The following conclusions can be drawn:

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In surface-bounded ducts, divergence loss may be treated as spherical for approximately the first 1000 to 1500 yards, and as cylindrical thereafter. Beyond a few thousand yards, attenuation is the predominant loss at 10 kc. This loss is comprised about equally of absorption and of leakage out of the duct.

Ducts may be catalogued as standard, or as a definite number of steps better or worse than standard. Duct quality depends upon duct depth, temperature, temperature gradient (small) in the duct, and sea state.

Target strength of guppy submarines, as measured at 10 kc, ranges from 10 db at bow and stern aspects to 30 db at beam aspect.

Fluctuation in target strength from ping to ping is so large that obtaining several chances at an echo in sweeping through the target would be highly beneficial. The technique of transmitting several successive pings on different frequencies, as with the frequency-scanning technique, takes advantage of short-period fluctuation.

Signal processing techniques were advanced in this problem. Definite approaches for further advances are indicated.

Echoes over a bottom-reflected path were rare. While results over this path are not encouraging, there remains a definite possibility that lower-frequency equipment can capitalize on this path.

No evidence was obtained that the shallow-water problem is any different than the deep-water problem in surface-bounded ducts at 10 kc. Under adverse temperature gradients, shallow water sometimes permitted echo-ranging via the bottom. These statements are based on observations in the Key West area only.

The completion of this program is a milestone in the pursuit of truly long sonar range. Continuing vigorous prosecution of the search problem may lead to echo ranges of hundreds of miles.

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VI - RECOMMENDATIONS

The research thus far carried out has only scratched the surface of potential detection capability. It is recommended that lower-frequency performance down to one kilocycle be investigated with even greater thoroughness than has characterized the 10-kc work.

It is known that absorption reaches such a low value at 1 kc as to be practically negligible. Therefore, the choice of frequency below 1 kc cannot be justified on the basis of lower absorption, unless ranges of several hundred miles are sought. However, to exploit the use of bottom-reflected energy and energy penetrating into shadow zones, investigation of echo-ranging in the very low-frequency region is recommended.

It is recommended that oceanographic and propagation data, particularly in the 1- to 10-kc frequency band, be systematically catalogued, and that correlation of propagation loss with oceanographic data be carried out.

Propagation loss, noise level, and reverberation level, should be studied as functions of frequency and geographic locations. In particular, the problem of shallow-water propagation deserves special consideration in the Navy's research program.

The success obtained with special receivers leads to the recommendation that continuing effort be placed on signal-processing studies. The marrying of the Time-Delay and Frequency-Scanning receivers is recommended. (This is planned in the NRL 5-kc system). Other methods of obtaining high gain by high resolution in frequency and in time should be sought. Techniques for eliminating "wow" from recorded signals at playback should be perfected.

New methods of supplying power to the transducer should be developed. Ultimately, the power for long-range detection equipments should probably be supplied at signal frequency direct from an alternator. This method is incorporated in the NRL 5-kc equipment.

Research is needed on the maximum power per unit volume which active transduction materials can theoretically transduce, on the factors which limit, and on techniques for approaching the theoretical limit. The role of passive transducer material must not be overlooked. Close coordination between laboratories seems essential.

Many other problems are evident. The adaptation of low-frequency sonar to the surface ship, the problem of maximum area coverage and its dependence on beamwidth, and the ultimate direction of towed sonar as transducers become larger and larger are examples. It is recommended that these problems receive further consideration.

From the point of view of fleet readiness, it was already certain, at the conclusion of the experimental work herein reported, that vast forward strides in detection could now be confidently expected by going in the direction of larger transducers, higher power, and lower frequency - all three in combination. This knowledge was immediately conveyed to the bureaus in conferences and has influenced the design of fleet equipment, some of which is now installed.

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APPENDIX A - GEOMETRY OF SOUND RAYS IN DUCTS

DIVERGENCE IN DUCTS

The limit ray contained in a surface bounded duct, with a source just below the surface, is radiated from the transducer at an angle θ_1 above or below the horizontal. In practice θ_1 is small, about 0.05 radian, and the radiation may be considered uniform between plus and minus θ_1 .

With a uniform velocity gradient every ray will be an arc of a circle of radius ρ given by

$$\rho = \frac{c}{dc/dy} \quad (A-1)$$

in which c is sound velocity and y is depth. The length of arc from the surface to the boundary along the limit ray has been called X_1 . From simple geometry

$$X_1 = \rho \theta_1 \quad (A-2)$$

(Likewise for any ray in the duct $X = \rho \theta$) (A-2a)

Since θ_1 is not generally known, it will be expressed in terms of h through the trigonometric relation

$$h = \rho (1 - \cos \theta_1) = \rho \frac{\theta_1^2}{2} \quad (A-3)$$

The approximation is good for the small angles involved.

Eliminating ρ by employment of Eqs. (A-2) and (A-3), there is obtained

$$X_1 = \frac{2h}{\theta_1} \quad (A-4)$$

Simple extension of the theory to the case where the transducer is at depth y_1 , yields instead of (A-4)

$$X_1 = \frac{2(h - y_1)}{\theta_1} \quad (A-4a)$$

Confining attention to the case where the transducer is at the surface, and considering only rays which start below the horizontal, $10 \log (h/\theta_1)$ is the total divergence experienced in a vertical plane since all the rays confined to the duct spread from a vertical height θ_1 in radians, at one yard from the source, to a vertical height h and thereafter remain in the vertical height h . This fact, combined with (A-4) gives

$$\text{Divergence in vertical plane} = 10 \log \frac{X_1}{2} \quad (A-5)$$

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When the divergence in the horizontal of $10 \log r$ is added in, the total divergence is

$$\text{Total divergence loss} = 10 \log \frac{X_1}{2} + 10 \log r = 20 \log \frac{X_1}{2} + 10 \log \frac{r}{X_{1/2}} \quad (\text{A-6})$$

i.e., divergence is equivalent to spherical to X_1 , given by Eq. (A-2), and cylindrical thereafter.

The loss is decreased, however, by the addition of energy radiated above the horizontal and reflected from the surface. This decrease in loss is covered by subtracting 3 db from the divergence loss of Eq. (A-6) to give

$$\text{Total divergence loss} = 20 \log \frac{X_1}{2} + 10 \log \frac{r}{X_{1/2}} - 3 \text{ db} \quad (\text{A-6a})$$

ENERGY INCIDENT ON THE SURFACE

It is assumed that reflection out of a duct is proportional to the fraction of energy incident on the surface per unit distance of travel, that is, proportional to $1/2X$ or by equation (A-2a) to $1/2 \rho \theta$ for any bundle of rays about θ .

If we divide the radiated energy into increments $dW = W(\theta) d\theta$, then the energy incident per unit distance summed for all increments is given by

$$\frac{W_i}{R} \propto \int_0^{\theta_1} \frac{W(\theta) d\theta}{\rho \theta} \quad (\text{A-7})$$

where W_i is energy incident on the surface and R is the distance in kiloyards. The total energy in the duct is W given by

$$W = \int_0^{\theta_1} W(\theta) d\theta \quad (\text{A-8})$$

(A-7) divided by (A-8) gives the fraction of total energy incident per unit distance. This is

$$\frac{W_i}{WR} \propto \frac{\int_0^{\theta_1} \frac{W(\theta) d\theta}{\rho \theta}}{\int_0^{\theta_1} W(\theta) d\theta} \quad (\text{A-9})$$

If $W(\theta)$ is a constant, (A-9) becomes infinite which implies that energy must redistribute very rapidly, away from $\theta = 0$. It can be shown, based on certain assumptions, that at long range $W(\theta) = k\theta$, a stable distribution, where k is a constant. Substituting this in (A-9) yields upon integration

$$\frac{W_i}{WR} \propto \frac{1}{\rho \theta} = \frac{1}{\sqrt{\rho h}} \quad (\text{A-10})$$

The leakage coefficient, α_L , is therefore proportional to $1/\sqrt{\rho h}$.

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APPENDIX B - LIST OF SYMBOLS

R	is range in kiloyards
R_0, R_1, R_2	are specific values of R
r	is range in yards
α	is attenuation coefficient (total) in db per kiloyard
α_0	is absorption coefficient in db per kiloyard
α_L	is leakage coefficient in db per kiloyard
α_k	is the reverberation leakage coefficient in db per kiloyard
f	is frequency in kilocycles per second
E	is echo excess, the excess in decibels of the echo level above the level required for 50% detection
E_1	is the hypothetical value of E at a range of 1 yd
E_R	is the echo excess, relative to reverberation
I_1	is the intensity at 1 yd from the source, relative to an intensity corresponding to an rms pressure of 1 microbar
I_e	is the intensity of the returned signal (echo) at the transducer face
T	is the target strength
T'	is the simulated target strength
N	is the omnidirectional noise in a one cycle band
L	is the total one way transmission loss in db
L_D	is the transmission loss due to divergence or spreading
L_0	is the transmission loss due to absorption
L_L	is the transmission loss due to leakage
Δ	is the directivity index
δ	is the recognition differential: i.e., the ratio of signal to noise in a one cycle band, at the transducer output required for 50% probability of detection
δ_R	is the recognition differential relative to reverberation

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t is the temperature in degrees Fahrenheit

τ is the signal pulse length in seconds

BW is the bandwidth between the 10 db down points

ρ is the radius of curvature of the sound ray

ρ_1, ρ_2 numerical values of ρ

h is the duct thickness

S is the numerical value of the sea state

X_1 is the horizontal distance in yards between the point at which the limit ray impinges on the water surface, and the point at which the ray becomes tangent to the lower boundary of the (surface-bounded) duct

X is the comparable distance for a ray which makes an angle θ with the horizontal

θ_1 is the angle the limiting ray makes with the horizontal at the water surface

θ is the angle any ray makes with the horizontal at the water surface

K is the average reflection loss per reflection in db

n is the number of reflections

c is the velocity of sound

y is the depth

y_1 is a particular value of y

W is the total radiated acoustic energy in the surface-bounded duct

W_1 is the radiated acoustic energy incident on the water surface

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UNITED STATES GOVERNMENT
memorandum

7103/131

DATE: 12 November 1996

FROM: Burton G. Hurdle (Code 7103)

SUBJECT: REVIEW OF REF. (a) FOR DECLASSIFICATION

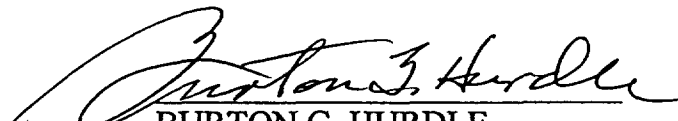
TO: Code 1221.1

VIA: Code 7100

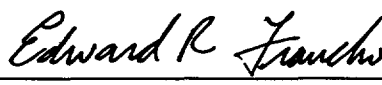
AD-889 324

REF: (a) NRL Report #4515 by H.L. Saxton et al, 19 Aug 1955 (U)
(b) NRL Ltr 2028-526 of 5 Oct 1966

1. Reference (a) is a discussion of the test conducted and the performance of the 10-kc long-range search sonar. The 10-kc active sonar was one of the phases in the reduction of the operating frequency of active sonars following World War II. The major frequency of sonars during World War II was 25 kHz. The research and development at NRL following the war progressed to 10 kHz, 5 kHz, and 2 kHz. This report includes the design of the system and at-sea test results.
2. This technology and equipment of reference (a) have long been superseded. The current value of this report is historical.
3. Reference (a) was declassified by reference (b).
4. Based on the above, it is recommended that reference (a) be released with no restrictions.


BURTON G. HURDLE
Acoustics Division

CONCUR:

 11/12/96
EDWARD R. FRANCHI Date
Superintendent
Acoustics Division

Completed
1-18-00
B.W.